The Diffusion of Environmental Innovations: A Geographical Perspective on Lead Markets and Technology Licensing in China

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Abstract

The consequences of the climate crisis for life on earth are already severe. In addition, the planet is facing a multitude of other negative environmental impacts of human activity, including the loss of biodiversity, the depletion of resources and environmental pollution, to name but a few. In response to these great challenges, there has been extensive research over the last few years directed towards the development of environmentally friendly technologies. These so-called green technologies or environmental innovations include, among other things, renewable energy technologies, energy-efficiency technologies and waste management technologies. In order to tackle the climate crisis and environmental damage, however, it is not sufficient simply to invent green technologies; they must also be used and diffused globally.

In this dissertation, I shed light on the diffusion of environmental innovations from a spatial perspective, i.e. the process from invention to adoption and the geography thereof. My research focuses on diffusion processes taking place in China, which is a particularly important case. The pace of China's sustainability transition will have a decisive impact on global futures given its current environmentally adverse modes of production and consumption. At the same time, China ranks as the largest market for green technologies and leads the technological frontier in many domains. From an economic geography point of view, many Chinese regions therefore enjoy great prospects for green regional path development, which might lead to a win-win situation for the environment and the local economy.

Against this background, I analyze the diffusion of environmental innovations in Chinese regions using a regional case study and quantitative analyses of patent licensing data. Drawing on the case study, I develop a conceptual framework that provides a rationale for the spatial diffusion of environmental innovations: the regional lead market framework. The quantitative analyses provide statistical evidence for how spatial patterns of green technology diffusion might evolve into lead market structures. The findings reveal, inter alia, that geographic proximity between innovators and adopters not only increases the likelihood of innovation diffusion processes, but also their speed. The results of this dissertation yield important lessons for regional eco-innovation policy.

Keywords: Sustainability Transitions, Environmental Innovation, Regional Development, China, Patent Licensing, Lead Market

Zusammenfassung

Die Klimakrise hat gravierende Folgen für das Leben auf der Erde. Darüber hinaus ist der Planet mit einer Vielzahl weiterer negativer Umweltauswirkungen menschlichen Handelns konfrontiert, darunter der Verlust der Biodiversität, die Erschöpfung von Ressourcen sowie Umweltverschmutzungen, um nur einige zu nennen. Als Reaktion auf diese Herausforderungen wurde in den letzten Jahren umfangreich an umweltfreundlichen Technologien geforscht. Zu diesen sogenannten grünen Technologien bzw. Umweltinnovationen gehören beispielsweise regenerative Energiequellen, Energieeffizienztechnologien oder Abfallbehandlungstechnologien. Um der Klimakrise und Umweltschäden entgegenzuwirken, reicht es jedoch nicht aus, grüne Technologien zu entwickeln, sondern sie müssen auch weltweit eingesetzt werden und diffundieren.

In dieser Dissertation untersuche ich die Diffusion von Umweltinnovationen aus räumlicher Perspektive, d.h. ich analysiere den Prozess von der Erfindung bis zur Anwendung von grünen Technologien sowie die Geographien dessen. Meine Forschung konzentriert sich auf Diffusionsprozesse in China, da China aufgrund der gegenwärtigen umweltschädlichen Produktions- und Konsumweisen eine kritische Rolle für die globale Nachhaltigkeitstransition spielt. China ist gleichzeitig auch wichtigster Markt für grüne Technologien und in vielen umweltrelevanten Bereichen technologisch führend. Aus wirtschaftsgeographischer Perspektive bieten sich daher für viele chinesische Regionen vielversprechende Chancen für eine grüne Regionalentwicklung, die positive Effekte sowohl für die Umwelt als auch für die lokale Wirtschaft und Bevölkerung miteinander vereinbart.

Vor diesem Hintergrund analysiere ich die Diffusion von Umweltinnovationen in chinesischen Regionen anhand von einer regionalen Fallstudie und quantitativen Analysen von Technologielizenzen zu grünen Patenten. Auf Basis der Fallstudie erarbeite ich das Konzept der Regionalen Leitmärkte, das eine Begründung für die räumliche Verbreitung von Umweltinnovationen liefert. Die quantitativen Analysen präsentieren statistische Hinweise dafür, wie sich räumliche Diffusionsmuster grüner Technologien zu Leitmarktstrukturen entwickeln können. Die Ergebnisse zeigen unter anderem, dass die räumliche Nähe zwischen Innovatoren und Anwendern nicht nur die Wahrscheinlichkeit von Innovationsdiffusionsprozessen erhöht, sondern auch deren Geschwindigkeit. Die Ergebnisse dieser Dissertation liefern wichtige Erkenntnisse für die regionale Umweltinnovationspolitik.

Schlagworte: Nachhaltigkeitstransition, Umweltinnovation, Regionalentwicklung, China, Patentlizenz, Leitmarkt

Acknowledgments

'How do we sleep while our beds are burning?'

(theme track at COP15 in Copenhagen, 2009)

Während in Glasgow gerade die COP26 endet, sitze ich an meinem Schreibtisch und denke über die abschließenden Worte dieser Dissertationsschrift nach. Die in Schottland diskutierte Klimakrise ist die größte Herausforderung unserer Zeit und gute Wissenschaft stellt die Grundlage dar, um deren Ursachen und Wirkungen zu verstehen und Lösungswege aufzuzeigen. Daher bin ich sehr dankbar für die Chance, dass ich mich die vergangenen drei Jahre in meiner Forschung mit der Diffusion von Umweltinnovationen und Nachhaltigkeitstransformationsprozessen in China auseinandersetzen durfte und somit einen kleinen Beitrag zum Verständnis einer umweltfreundlicheren Zukunft leisten konnte.

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CHAPTER ONE

Introduction

1.1 Motivation

The world is currently facing severe challenges brought about by human-environment interaction. Species are becoming extinct, biodiversity is decreasing, pristine natural areas are shrinking, finite natural resources are being depleted, and the pollution of the environment and the oceans is evident all over the world. Probably the greatest contemporary societal challenge, however, is the climate crisis. Climate change is exacerbating already existing environmental problems, and in the-worst case scenario, probably has too many detrimental consequences to list in this dissertation.[1]

At the same time, numerous technological solutions already exist that can help to combat climate change and its consequences, as well as other environmental concerns. The development of renewable energy technologies is probably the most straightforward example in this regard, with installed capacity steadily increasing. In addition, many products are becoming more resource and energy efficient, research is being conducted into environmentally friendly alternatives to CO_2-intensive products such as cement, and there are even technologies to capture and store greenhouse gases, to name but a few examples. It is evident that humankind has become very proficient in recent years at developing such environmentally friendly technologies and, from an innovation studies perspective, has become very adept at understanding how to foster the development of green technologies. Unfortunately, humans are not yet good enough to enforce the application and diffusion of environmentally friendly technologies. However, in order to counteract the above-mentioned environmental (and societal) challenges, it is necessary not only for innovations to emerge, but also for them to diffuse on a large scale. Given the social embeddedness of environmentally friendly technologies and the structural barriers to their diffusion, a so-called socio-technical transition will be needed to establish more sustainable modes of production and consumption (Markard, Raven, & Truffer, 2012).

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[1] Please refer to the latest IPCC synthesis report for an overview of climate change impacts (IPCC, 2014). The updated synthesis report (6th assessment) will be published in 2022.

These perceptions on climate change and environmentally friendly technologies bear an explicit geographical imprint. While climate change is a global concern, it will have particularly severe consequences for certain countries and regions (Peri & Robert-Nicoud, 2021). On the other hand, the main contributors to climate change encompass only a few countries and regions. Paradoxically, the regions responsible are not the ones suffering the most, making climate change an inherently unjust phenomenon. The research and development of environmentally friendly technologies that might mitigate climate change is also taking place in only a few countries and regions with sufficient capacity to do so. However, the application of green technologies is not limited to these places, turning climate action into a global task. From an economic geography perspective, numerous complex spatial issues can be identified in light of these considerations, some of which are addressed in this dissertation.

One of the most interesting places for studying the phenomena described above is the People's Republic of China. China is often blamed as the primary culprit of the climate crisis. This assertion is mostly substantiated using the fact that China is currently the largest emitter of CO_2 and other greenhouse gases, accounting for over a quarter of new global CO_2 equivalent emissions each year since 2010. Yet when considering per capita emissions, statistics change and Western countries might in fact be to blame for major portions thereof.[2] According to research on historical climate debts that quantifies the accumulated carbon emissions of nations using fair shares (through 2015), China is actually an undershooter (‘climate creditor’) and thus less responsible for the climate breakdown, while the USA and EU-28 are overshooters (‘climate debtors’) and account for 40 and 28 percent of climate responsibility respectively (Hickel, 2020; see also Matthews, 2016). These figures, of course, are subject to change as China has not yet peaked in terms of annual total emissions. Generally speaking, responsibility for climate change is a complex issue, with China remaining the focus of international climate policy regardless of (historically fair) statistical attributions. Kopra (2018) describes the social process of China being discussed on the international stage as the main culprit for the climate crisis as *responsibilization*. Although China is not the main bearer of responsibility for the climate crisis, nor has it wanted to shoulder this responsibility in recent years (although this is currently changing), it is being assigned climate stewardship. In fact, China recently announced a goal to peak emissions before 2030 and be climate neutral by 2060, making China a key player on which the planet’s

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[2] A very useful tool for descriptive analyses of greenhouse gas emissions (among other kinds of data) can be explored at www.ourworldindata.org (Ritchie & Roser, 2020).

fate depends (Mallapaty, 2020). As a matter of fact, China is already among the leading nations in green technology development and production, with some regions also pioneering their application (Ely, Geall, & Dai, 2019; Huang & Lema, 2021; Lauer & Liefner, 2019; Walz, Pfaff, Marscheider-Weidemann, & Glöser-Chahoud, 2017).

In this dissertation, I wish to contribute to the understanding of how green technologies diffuse across time and space, providing some lessons learned from the Chinese case. In that regard, I hope that this dissertation will make a small contribution to help reduce the adverse impact of human activity on our planet.

The remainder of this dissertation is structured as follows. The following section will introduce the theoretical background underlying this dissertation, also presenting the research objectives. I will then provide a brief background on China's role in sustainability transitions, extending some of the arguments discussed above. After that, data and methodology will be explained, while an overview of the research projects included in this dissertation concludes the introductory chapter. The subsequent chapters comprise four research articles and a short graphic article, forming the main part of this dissertation. In the conclusion, I summarize the main findings of these articles in light of the research objectives. Thereafter, I describe the limitations of my research and derive implications for both theory and policymaking. Finally, I propose avenues for further research.

1.2 Theory and research objectives

1.2.1 Environmental innovation: peculiarities and stylized facts

The social science approach to innovation dates back to early work by Schumpeter (Schumpeter, 1934). Since then, a research field of innovation studies has been established which deals with various questions surrounding the topic of innovation and examines, among other things, different types of innovations, including environmental innovations. Environmental innovations are those innovations that help reduce negative environmental impacts or create environmental benefits.

In innovation studies, there are numerous theories and concepts that help to better understand what innovation is all about, much of which can also be applied to environmental innovations. Critics sometimes argue that environmental innovations merely describe a kind of cross-sector for which there is no need for an independent theory or research sub-field. Pertinent research, however, makes clear that concepts from innovation studies require adaptation in order to accommodate the specificity of environmental innovations. Examples include the concept of lead markets for environmental innovations (Beise & Rennings, 2005b) or the notion of the open-eco innovation mode (Ghisetti, Marzucchi, & Montresor, 2015), both of which are based on older ideas from innovation studies (lead markets, open innovation) (Beise, 2004; Chesbrough, 2003). In addition, a revised concept of green windows of opportunity has recently entered the debate on latecomer development (Lema, Fu, & Rabellotti, 2021). The fact that there is demand for distinct (or adapted) concepts that contribute to analyzing environmental innovations from a social science perspective results from various peculiarities of environmental innovations and several stylized facts that have been gathered in the past couple of years of research. This burgeoning literature contributes not least to the establishment of a distinct research field and an international research community focused on environmental innovations (see, for example, Kemp et al., 2019). This section serves to outline the main peculiarities of environmental innovations as well as some selected stylized facts. First, however, it is necessary to define what environmental innovations actually entail and what they refer to in the context of this dissertation.

There are numerous terms that are used to label environmental innovations such as green innovation, eco-innovation or sustainable innovation, among others. Although there are differences in the exact definitions, these terms are widely used interchangeably in practice (sometimes even by the same authors). A number of studies deal with the taxonomy of the above-mentioned terms in great detail (Franceschini, Faria, & Jurowetzki, 2016; Schiederig, Tietze, & Herstatt, 2012). This dissertation will not re-enter into that debate, with the notion of environmental innovations following a relatively recent and rather broad definition: '*An eco-innovation 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 & 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 innovations according to the degree of environmental impact or they might explicitly include social or organizational innovations as well.[3] That said, the use of the term environmental innovation in this dissertation is largely limited to green technologies and disregards other forms of innovation (e.g., business models). I thus deviate slightly from the above-mentioned definition. The empirical analyses in this dissertation draw on the OECD's ENV-TECH classification to operationalize environmental innovations (Haščič & Migotto, 2015).

As previously stated, green technologies and environmental innovations 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. The adopter contributes to reducing negative environmental impacts. While this has a non-excludable positive effect on other organizations and on society as a whole, the adopter alone bears the costs. Accordingly, this double-externality problem causes firms and other organizations to underinvest in environmental innovations (Beise & Rennings, 2005a; Rennings, 2000).

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, the regulatory push/pull, is required to stimulate environmental innovations (Rennings, 2000). In some areas, such as the energy sector, environmental innovations face a further barrier (triple regulatory challenge), as existing infrastructures and monopolistic bottlenecks in the energy sector can often only be resolved through additional regulatory measures (Walz, 2007).

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[3] A list of some common definitions for environmental innovations is provided in Kemp et al. (2019, p 158-159).

Environmental 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. For example, regulations that control the use of resources can simultaneously lead to lower costs for product development. 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 & van der Linde, 1995; Rexhäuser & Rammer, 2014).
Alongside these peculiarities derived from theoretical work, empirical research on environmental innovations has also uncovered a number of stylized facts that can be used to differentiate them from regular innovations. That is to say, environmental innovations differ from regular innovations in terms of complexity and impact. On the one hand, they rely on more diverse knowledge and combine more technological components. They therefore require a higher degree of R&D cooperation and external knowledge in the developmental phase (De Marchi, 2012; Ghisetti et al., 2015), which is also reflected in greater team efforts needed for inventing as well as positive effects of involving academic inventors (Orsatti, Quatraro, & Pezzoni, 2020; Quatraro & Scandura, 2019). Regional characteristics play a decisive role in this context, as spatial proximity to universities and research centers shows a stronger positive effect for environmental innovations than for regular innovations (Horbach, 2014). On the other hand, they have a stronger impact on future innovations (Barbieri, Marzucchi, & Rizzo, 2020; Orsatti, Quatraro, et al., 2020).

However, environmental innovations and green technologies do not form a homogeneous group. Instead, they can be further subdivided on the basis of various characteristics, e.g. distinctions based on technological domains (ENV-TECH), distinctions between end-of-pipe and cleaner production technologies (Frondel, Horbach, & Rennings, 2007), distinctions based on scale between infrastructure innovations and consumer goods (Walz, 2007; Wilson et al., 2020), among others. Most of the peculiarities and stylized facts are, however, common to all environmental innovations.

It is not, after all, the case that environmental innovations should be treated as a panacea for solving global challenges such as climate change. This is particularly important to bear in mind since the concept of environmental innovation carries a strong normative character. That is to say, the terms ‘innovation’ and ‘environmental/sustainable’ both have a positive connotation, making environmental innovation a controversial concept and suggesting that it is – normatively - ‘good’ (Godin & Gaglio, 2019). As a matter of fact, some environmental innovations have only relatively positive effects, as they might for instance reduce emissions of greenhouse gases, but do not prevent them. There are also some environmental innovations, for example as in the fields of renewable energies or e-mobility, that create other sustainability conflicts, since rare-earth metals and other scarce resources might be needed for production (U. E. Hansen, Nygaard, & Dal Maso, 2021; J. C. K. Lee & Wen, 2018). Many innovations that could help to mitigate climate change such as nuclear energy or carbon capture and storage (CCS) technologies are highly contested, making it difficult to balance environmental goals with ethical issues. Additionally, the government's subsidization of environmental innovations or possible cost advantages of sustainable products may have adverse consequences. This negative outcome from cheaper or more efficient sustainable goods is what is known as the rebound effect. If an environmentally friendly product is offered at a low price, this may lead to a higher per capita consumption of this product, which may ultimately have a more negative impact on the environment than the consumption of a more expensive but less environmentally friendly product (direct rebound effect or substitution effect). An indirect rebound effect can occur when the lower cost of an environmentally friendly product leads to those cost savings being used to consume other (non-environmentally friendly) goods or services (Freire-González, 2017; Lange, Kern, Peuckert, & Santarius, 2021; van den Bergh, 2011). The aforementioned negative consequences of environmental innovations should be kept in mind when interpreting the results of this dissertation. At the same time, I would like to refer to a rapidly growing body of literature that deals with the dark sides of (environmental) innovation (Coad, Nightingale, Stilgoe, & Vezzani, 2021).

1.2.2 Green regional path development and the geography of sustainability transitions

In geography-related research on environmental innovations, two main foci have been established in the last couple of years. One deals with the spatial drivers and outcomes of green industries, applying a supply-side perspective. The other deals with the demand side, analyzing the adoption and diffusion of environmental innovations needed for a transition towards more sustainable futures (Hansmeier, 2021).

On the supply side, research and development of environmental technologies holds great potential to create jobs and to generate economic value. As a result, green industries are often construed as an engine for growth. The ‘green growth’ narrative hence suggests that regional economic development can benefit from green industries, aligning economic and ecological goals (Capasso, Hansen, Heiberg, Klitkou, & Steen, 2019; Jänicke, 2012). Employment in green industries can, in fact, have a multiplying effect and can be linked to the creation of additional jobs in a region. Moreover, regions in which green industries thrive are less affected by external economic shocks, meaning that green industries improve regional economic resilience (Vona, Marin, & Consoli, 2019). However, because green industries typically involve specialized jobs and rely on higher levels of human capital, they present uneven opportunities for regions with varying factor endowments (Consoli, Marin, Marzucchi, & Vona, 2016; Sofroniou & Anderson, 2021). Countries and regions with strong green industries, exporting complex green goods, are also found to have increased capabilities to further innovate in green technologies while having lower CO_2 emissions (Mealy & Teytelboym, 2020). At the same time, diversifying into green industries presents lagging regions with the opportunity to tap into new growth potential and to catch up or leapfrog to the technological frontier (Binz, Truffer, Li, Shi, & Lu, 2012; Quitzow, Huenteler, & Asmussen, 2017). In that respect, so-called green windows of opportunity might provide the initial impetus for green industry development in a latecomer context (Lema et al., 2021).

Put simply, green path development offers a promising way to boost regional economies. Different types of regions, however, have quite different capabilities to harness this potential (Grillitsch & Hansen, 2019). This literature on green regional development, mainly written by economic geographers, explores ways to green the local industrial structure. For instance, Santoalha & Boschma (2021) show that regions are more likely to diversify into green industries when existing regional capabilities are related, with policy support playing a moderating role. This also means that green regional paths can emerge from old and dirty industries (Fornahl, Hassink, Klaerding, Mossig, & Schröder, 2012; van den Berge, Weterings, & Alkemade, 2020). However, the processes by which green pathways unfold are not uniform and can occur, for example, as path renewal, path diversification, path creation or path importation (Trippl, Baumgartinger-Seiringer, Frangenheim, Isaksen, & Rypestøl, 2020). In this context, change agency can play a major role in the development of green industries, for instance through place-leadership or institutional entrepreneurship (Sotarauta, Suvinen, Jolly, & Hansen, 2021). It is also important to consider that linkages between different pathways exist across varying regional contexts, making (green) path development a highly complex phenomenon (Frangenheim, Trippl, & Chlebna, 2020). In light of these scholarly discussions, regional innovation policy can design measures to establish new or to strengthen existing green industries (Tödtling, Trippl, & Frangenheim, 2021).

However, the focus in this emerging strand of literature rests on the supply side of environmental innovations, namely invention and production. The positive effects on the environment, of course, only unfold on the demand side, i.e. during application and diffusion of environmental innovations.

In order to investigate these demand-side processes, a field of research has been established over the past two decades that deals with the long-term and complex transformation towards more sustainable modes of production and consumption, known as sustainability transitions (Köhler et al., 2019; Markard et al., 2012). The fact that existing environmental innovations have not yet spread to a scale capable of solving the climate crisis and avoiding other environmental problems seems paradoxical. An essential premise for understanding this issue is that technologies are embedded in so-called socio-technical systems. These socio-technical systems, e.g. the energy system, are shaped by rigid structures, i.e. regimes. Destabilization of these regimes, for example to embrace more sustainable systems, can result from the pressure and growth of niches, such as radical environmental innovations. This approach is known as the multi-level perspective on sustainability transitions (Geels, 2004, 2011). Another theoretical approach, technological innovation systems, attempts to describe how certain (green) technologies emerge. Here, functions such as resource mobilization and knowledge creation play a role, as do market formation and legitimization processes (Jacobsson & Bergek, 2011; Markard, Hekkert, & Jacobsson, 2015). These concepts, as well as most empirical research in sustainability transitions, have long been blind to the role of geography, i.e. places, scales and space (Binz, Coenen, Murphy, & Truffer, 2020; Coenen, Benneworth, & Truffer, 2012; Markard et al., 2012; Quitzow, Walz, & Köhler, 2014; Truffer & Coenen, 2012).

In recent years, however, the importance of geography has been increasingly emphasized, and a group of researchers has coalesced to focus explicitly on the geography of sustainability transitions.[4]

Geography plays an essential role for transitions due to place-specificities, for example. Urban and regional visions and policies can contribute to the upscaling of niches and green path development. At the same time, regions differ in their technological and industrial specialization, some of which focus on green industries (see above). Local natural resources determine how transitions unfold and vary among regions, for instance as a result of favorable conditions for wind energy. Informal localized institutions such as regionally embedded social practices and norms further contribute to differing regional transition dynamics. On the demand side, local market formations and local consumers might facilitate or hamper regional transitions towards sustainability (T. Hansen & Coenen, 2015). While these arguments support the regional dimension of transitions, a parallel discussion is taking place on the multi-scalarity of innovation systems and transition processes, which is expressed not only through the interconnectedness of different regional entities (regions, nations, etc.), but also through linkages on different scales. These considerations have led to the conception of global innovation systems and the regional configuration thereof (Binz & Truffer, 2017; Rohe, 2020). The multi-scalarity of transition processes results in regional transitions constantly being fragile and dependent on both endogenous and exogenous forces (Chlebna & Mattes, 2020).

This brief overview identifies two streams of research that address the geography of environmental innovation. On the one hand, the literature on green regional path development focuses on the supply side and mainly addresses the question of how the invention and production of environmental technologies can be used as an engine for regional development. The literature on the geography of sustainability transitions, on the other hand, is more concerned with the demand side and attempts to establish how different spatial scales are instrumental in driving the deployment of environmental innovations. A subordinate goal of this dissertation is to approach both fields of research in tandem to better understand the role of geography for environmental innovation and to stimulate cross-fertilization between these research streams.

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[4] Since 2021, for example, there has been a thematic group within the large sustainability transitions research network (STRN) which goes by the label GeoST. Although this community was formerly known as GOST, the search for a suitable acronym seems to be more difficult than the actual collaboration and consolidation, which is expressed through dedicated webinar series, workshops, special sessions at conferences, a working paper series and special issues in leading journals.

1.2.3 Spatial innovation diffusion and the notion of lead markets

Apart from the topics addressed so far (environmental innovations, green path development, geography of sustainability transitions), there is a rich body of research on innovation diffusion that does not focus on sustainability issues. The origins of this research field can be traced back to pioneering work by Rogers (1962), who focused in particular on the social aspects of diffusion and defined different groups of adopters based on the speed of adoption of an innovation, such as early adopters, who make use of innovations at a very early stage and help to mainstream the diffusion process. In this regard, the diffusion of innovations usually follows a sigmoid curve (typical S-curve), which can be described with logistic functions (Griliches, 1957). Other diffusion models, such as the Bass model, are based on epidemic models and have recently attracted increasing attention outside the field of innovation research due to the COVID-19 pandemic (Bass, 1969).[5]

The very first explicitly geographical work on innovation diffusion, however, was conducted by Hägerstrand (1967), who used statistical models to reveal the dependence of the speed of innovation adoption on spatial proximity to the innovator. In response to the seminal work by Hägerstrand, there has been ample research that gathered further stylized facts on the spatial diffusion of innovations (Brown & Cox, 1971) as well as some critical reflections on a theory of (spatial) innovation diffusion in human geography (Blaikie, 1978). Ever since, numerous very sophisticated models have been developed to simulate the spatial process of innovation diffusion. For instance, Lengyel et al. (2020) show that innovations diffuse not only to proximate geographic places, but also to (distant) large agglomerations, from which they diffuse again to adjacent areas. At the same time, innovations are more prone to diffuse faster within distinct geographical clusters (Baptista, 2000, 2001).

There are several theoretical perspectives that can be considered for explaining the spatial diffusion of innovations in more detail. This dissertation mainly draws on the concept of lead markets. The concept was pioneered and developed by Beise (2004) in particular, but was also significantly influenced by other researchers (e.g. Meyer-Krahmer, 2004). A lead market is a country (or region) that first adopts a later successful innovation, building an early relative competitive advantage and strongly affecting the international diffusion of the respective innovation. Other countries or

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[5] A useful overview of innovation diffusion models is provided in Frenzel & Grupp (2009).

regions, i.e. lag markets, anticipate the benefits demonstrated by the lead market and follow by adopting the innovation. The lead market has the potential to steer further technological progress in the field and can capture large portions of the value chain through its early mover advantages. Given its demand-orientation, the concept of lead markets is highly attractive for innovation policy, while other key approaches, such as innovation systems, tend to focus on the supply side of innovations and ignore the actual domestic application of innovations for creating added value (Edler, Georghiou, et al., 2009; Meyer-Krahmer, 2004; Walz, Ostertag, Eckartz, Gandenberger, & Bodenheimer, 2019).

However, in order to become a lead market, a number of supporting factors need to come into play.[6] Firstly, price and cost advantages for a specific innovation are important drivers of the lead market potential. They might result from high growth rates, economies of scale and the costs for input factors. Secondly, demand advantages describing favorable demand conditions for an innovation design contribute to the lead market potential. Thirdly, a country or region that is able to influence the demand of an innovation in other markets exhibits so-called transfer advantages. This advantage is typically driven by demonstration effects and international (manufacturing) reputation. Fourthly, an export advantage enhances the potential to become a lead market. The export advantage might stem from similarities to foreign market conditions, anticipation of foreign demand preferences, and a general export orientation as well as export experience of local firms. Finally, the market structure advantage, denoting high levels of competition in the domestic market, will contribute to the lead market potential (Beise, 2004). For the special case of environmental innovations, however, the market structure advantage does not take effect owing to the double-externality problem (see above). In this case, a regulatory advantage based on the diffusion of successful local regulations serves as a substitute (Beise & Rennings, 2005b, 2005a). The focus on both demand-side and supply-side effects, as well as the explicit geographic scope and applicability of the concept for the case of environmental innovations, make this concept highly suitable as the theoretical backbone for this dissertation.

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[6] A more elaborate discussion of the concept of lead markets will be provided in article one, chapter two.

1.2.4 Research objectives: understanding the spatial diffusion of environmental innovations

The concept of lead markets is very useful for analyzing the spatial diffusion of environmental innovations and is widely referred to in empirical studies (e.g. Cleff & Rennings, 2016; Horbach, Chen, & Vögele, 2014; Köhler, Walz, Marscheder-Weidemann, & Thedieck, 2014; Lacerda & Van den Bergh, 2014; Rennings & Smidt, 2010). The premise of these studies is that lead markets emerge at the spatial level of nations that drive the international diffusion of environmental innovations. However, the aforementioned research on the geography of innovation, the geography of sustainability transitions, and on green regional path development suggests that subnational regions matter significantly for both innovation emergence and diffusion. So far, existing conceptual frameworks have not been sufficient to model the inter-regional diffusion of environmental innovations on a subnational level.

From a geographical perspective, the double externality problem adds to the complexity of diffusing environmental innovations. Due to the fact that environmental innovations are exposed to an additional externality in the diffusion phase, it can be assumed that regional demand effects and regional regulations are likely to strongly contribute to the adoption of environmental innovations in a given region. Accordingly, a regionalized framework for analyzing diffusion processes for environmental innovations is required that takes into account not only regional technological capabilities, but also regional demand and regulations, with the notion of lead markets offering a useful starting point. This regionalized framework will be useful for understanding the diffusion of environmental innovations and for advancing the perception of regional transition pathways. At the same time, such a framework will be instrumental to inform place-based eco-innovation policy. By setting a first research objective, this dissertation seeks to contribute to developing this framework.

Research Objective 1: *To develop a regionalized framework for the analysis of the spatial diffusion of environmental innovations (article 1)*

Given such a framework, it will be possible to derive hypotheses on the factors influencing the spatio-temporal diffusion of environmental innovations. However, it remains unresolved as to how these diffusion processes can be captured empirically. The current research on the geography of sustainability transitions mostly relies on (qualitative) case study evidence that fails to provide a generalizable picture of transition and diffusion patterns (Hansmeier, Schiller, & Rogge, 2021; Köhler et al., 2019). Studies that quantitatively address the diffusion of environmental innovations rely on surveys in selected regions and therefore cannot provide a holistic picture of the geography of innovation diffusion (Antonioli, Borghesi, & Mazzanti, 2016; Horbach & Rammer, 2018). At the same time, such studies tend to face the problem that they can only consider regional effects either in the region of innovation development or in the region of innovation adoption. The complex interplay and mutual interdependence of regions, which is supposed to be at the heart of diffusion research, is largely ignored. Particularly, for countries such as China, characterized by strong regional disparities in both technological capabilities and regional demand for environmental innovations as well as by heterogeneous regional environmental regulations, there is a substantial unmet need for research on the patterns and determinants of green technology diffusion. This dissertation aims to address this research gap in a second research objective.

Research Objective 2: *To analyze the patterns and determinants of spatio-temporal environmental innovation diffusion processes in China (article 2-4)*

The results obtained from research objective two will contribute to the understanding of regional drivers that influence the development and diffusion of environmental innovations. As such, this dissertation continues a series of recent research articles that examine various (regional) determinants of environmental innovation. However, existing research on regional factors relating to environmental innovation has not yet been synthesized and there is a lack of general understanding concerning which determinants take effect at the regional level. Against this background, this dissertation sets a third and final objective, namely to provide a critical overview of the regional determinants of environmental innovations.

Research Objective 3: *To critically appraise the role of regional determinants for environmental innovation development and diffusion (article 5)*

As part of this endeavor, a research agenda will be developed to identify promising directions for analyzing environmental innovations from a regional perspective. This agenda will be designed for researchers from core geographic fields such as human or economic geography, regional studies and regional science, but it will also be helpful for geographically interested researchers from environmental economics, innovation studies or sustainability transitions, among other fields.

1.3 Background: China’s role in sustainability transitions

Empirical studies on sustainability transitions and the diffusion of environmental innovations are mainly concerned with Western countries and regions, ignoring emerging economies such as China. Paradoxically, scholars also highlight the importance of these countries, especially China, when it comes to future prospects for environmental innovation and green technology development (Ely et al., 2019; Walz et al., 2017). There are a number of arguments as to why research on sustainability transitions and environmental innovation should shift its focus to China.[7] On the one hand, there are obvious, straightforward arguments: China is the world’s largest CO_2 emitter (IEA, 2021; Ritchie & Roser, 2020). Moreover, China’s economy is among the world’s largest, still experiencing significant growth rates. With the USA forfeiting its role in global environmental responsibility due to having (temporarily) withdrawn from the UN Paris Agreement under the Trump administration, China is often said to have been ‘put in the driver’s seat’ for environmental protection and fighting climate change, which is underlined by current debates on China’s responsibility for greening their Belt and Road Initiative. In addition, three non-obvious, latent lines of reasoning can be identified, which are discussed hereafter.

Firstly, Western economies are locked into fossil-fuel-based systems. Unruh (2000) argues that industrialized (Western) economies are stuck in such a carbon lock-in situation due to path-dependency driven by increasing returns to scale. This lock-in is institutional and technological in nature and causes market as well as policy failures. Therefore, the carbon lock-in is one of the most severe barriers for the diffusion of environmental innovations and impedes sustainability transitions. However, in emerging economies such as China, leapfrogging into greener technological systems is considered to be possible (Binz et al., 2012; Schroeder & Chapman, 2014). Moreover, China’s economy is not only large, but also continues to grow at high rates, which eventually mitigates the risk of lock-ins. In effect, it allows for the occupation of

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[7] Some paragraphs of this section were originally part of the article on regional lead markets (chapter two). We had to remove these parts during the review process owing to lack of space in the paper. Ingo Liefner has contributed to organizing the line of reasoning in this section as well as writing minor parts. This footnote serves to acknowledge these contributions.

different growth paths concurrently: exploiting the carbonized energy system on the one hand, and exploring environmentally friendly modes on the other.

Secondly, China is taking over global green technology leadership. In past decades, China's economic growth was based on low-cost production, exports and inward foreign direct investments with an innovation system focusing on technology transfer and catching up. In the 2000s, however, China managed to build indigenous innovation capabilities aiming to become an innovation nation (Gu, Lundvall, Liu, Malerba, & Schwaag Serger, 2009; Liefner & Losacker, 2020; Losacker & Liefner, 2020a; Y. Zhou, Lazonick, & Sun, 2016). At present, China is the leading country in total patent applications and, more importantly, among the leading countries in green technology patenting (according to WIPO and GreenTechDB). China is thus taking over global green technology leadership, which is driven in particular by the government's push towards indigenous innovation (Huang & Lema, 2021).

Thirdly, China's central and regional governments have a huge potential to steer environmental innovation emergence and diffusion due to promising policy shifts. Both emergence and diffusion of environmental innovation critically depend on adequate implementation of innovation policies (Veugelers, 2012). Hence, nations and regions that are able to employ environmental innovation policies effectively are likely to build up lead market advantages. In light of this, innovation policy theorizing currently follows several promising paradigms: on the one hand, there is a significant shift towards challenge- and mission-oriented policies to target global challenges. These challenges allow for the definition of specific missions that can be pursued by funding or supporting research and innovation projects (Mazzucato, 2018). Moreover, challenge-orientation for enhancing innovation demand offers potential to guide transitions processes (Boon & Edler, 2018). The challenge-orientation has been put into practice in China's current political paradigms. For instance, China's *13th and 14th Five-Year Plans* highlight the importance of tackling climate change and further environmental problems. In addition, China is setting out guiding principles on how to realize the sustainable development goals in its *National Plan on Implementation of the 2030 Agenda for Sustainable Development* as well as in its recent announcements to be carbon neutral before 2060. In addition, place-based innovation policies are widely recognized as being able to improve regional innovation capabilities and link regional innovation actors, thus facilitating both innovation development and innovation diffusion (Tödtling & Trippl, 2005; Tödtling et al., 2021). China has a long tradition of implementing such policies. Following a logic of 'tinkering', central and regional policymakers in China often establish model regions for testing new regional policies (Brehm & Svensson, 2020; Heilmann, Shih, & Hofem, 2013). Finally, public procurement instruments are being increasingly employed to drive demand and promote environmental innovation adoption. Based on that, public procurement can effectively spur innovation and guide future technological trajectories (Edler & Georghiou, 2007). The importance of central and especially local governments in the Chinese economy offers great potential for innovation and innovation diffusion driven by public demand. Therefore, public procurement and demand are key to guiding the adoption of innovation designs to build (green) lead markets in China (Edler, Corvers, & Liu, 2009; Yanchao Li, 2011). Moreover, public procurement is an effective tool for accomplishing mission-oriented innovation policies (Edquist & Zabala-Iturriagagoitia, 2012), and offers high potential to foster environmental innovation, leading transition processes towards sustainability (Cheng, Appolloni, D'Amato, & Zhu, 2018; Lauer & Liefner, 2019). I argue that China's central and regional governments have a huge potential to steer environmental innovation emergence and diffusion in that respect due to the comparatively strong regulatory and financial power to intervene in the market.

The interplay of China's policy-driven approach towards innovation and its hugely varying regional innovation potential becomes evident from many studies that analyze innovation in China from a regional perspective (Heindl & Liefner, 2019; Liefner, Kroll, Zeng, & Heindl, 2021; Wei & Liefner, 2012). China is characterized by high levels of spatial disparities regarding well-being and income, economic structures and growth potential, endowments with S&T and R&D resources, and innovation-related mindsets (Huggins, Luo, & Thompson, 2014; Kroll & Neuhäusler, 2020; J. Wang, Wei, & Lin, 2019). The supply-side and demand-side potential for making and using innovation thus varies dramatically more than in Western countries. China's different trajectories of fostering environmental innovation become evident from case studies. One example is provided by the city of Shenzhen with strong green industries and an active city government, both of which successfully promote the diffusion of new energy vehicles motivated by environmental concerns and the chance to establish technology leadership (Lauer & Liefner, 2019). Equally prominent is the example of the city of Qingdao, which hosts one of China's prominent eco-parks (Ghiglione & Larbi, 2015).

Based on the considerations outlined above, it appears that an analysis of innovation diffusion processes in China promises to yield results from which other nations might also draw valuable lessons. At the same time, it is important to consider China-specific characteristics, as top-down transition processes predominate over bottom-up initiatives. Given that China's path to more sustainable economic activities will have a considerable effect on global development, it is necessary to thoroughly comprehend its innovation (diffusion) processes.

1.4 Data and methodology

The research in this dissertation draws on both qualitative and quantitative data, with a focus on the latter. The methodological rationale behind the combination is rather straightforward and directly results from the nature of the research objectives. For the first research objective, i.e. conceptualizing a theoretical framework, Ingo Liefner and I applied an *illustrative case-study approach* (Yin, 2017). Our conceptualization relies on literature work, and the empirical case of waste management in Shanghai serves to demonstrate the framework. The illustrative case study, however, has been analyzed in great depth using data from patents, documents and interviews (see Figure A.3 in Appendix A). On-site visits have further deepened our knowledge of the case.

The second research objective, i.e. analyzing the patterns and determinants of environmental innovation diffusion, requires a quantitative approach. As discussed in section 1.2, this dissertation avoids mainstream research in sustainability transitions that uses case-study methods to study the diffusion of environmental innovations, as '(…) *the increasing wealth of case materials creates demands and opportunities for methodological approaches that reach for generic insights across cases*' (Köhler et al., 2019, p. 18). At the same time, quantitative research on the adoption of environmental innovations relies heavily on survey data, which is often not sufficient to adequately reveal spatial patterns of innovation diffusion since it mostly captures the places of adoption and not the place where innovations are developed (Antonioli et al., 2016). On the other hand, the literature on the geography of innovation has been very successful in identifying the locations of innovation emergence and in explaining corresponding spatial patterns (Balland & Rigby, 2017; Mewes, 2019). This literature, however, has been rather silent when it comes to studying the geography of innovation adoption. One possible explanation is the strong reliance on appropriate indicators and the field's obsession with patent data that can usually not be used to map innovation adoption or diffusion processes. Patents, in fact, are also far from being perfect indicators of innovation and tend to mirror inventions that do not necessarily find commercial application or translate into goods (Archibugi, 1992; Kleinknecht, Van

Montfort, & Brouwer, 2002). This weakness of regular patent data is particularly evident in the Chinese setting (Dang & Motohashi, 2015).

With a few tweaks, however, patents can be used to track the diffusion of innovations. Put simply, one needs to merge patent data with license agreement data (Nelson, 2009). License agreements are contracts in which one party (the licensor) authorizes another party (the licensee) to make use of a patented technology. Licensed patents have strong advantages over regular patent data. Firstly, license data have a filtering function to exclude patents that are not introduced to the market, i.e. inventions. Since supplier and buyer agree on a monetary value of the patented technology, an economic purpose is attributed to the patent, marking it as an innovation. Secondly, license agreements provide information on the time-to-adoption of an innovation when contrasting the date of patent application with the date on which the licensing contract is concluded. Since license agreements provide information on the licensee, it is also possible to map where the technology is adopted. Altogether, this kind of data allows for the study of time and location of both innovation development and innovation adoption. That being said, licensed patents are valid and reliable indicators for studying innovation diffusion. Figure 1 provides a graphical representation of how patent license agreements can be used as an indicator for innovation diffusion in that respect.

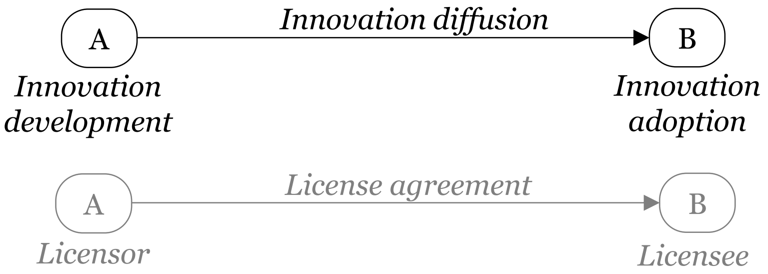

Figure 1: *Using patent license agreements as an indicator for innovation diffusion*

Unfortunately, licensing data is not publicly available and needs to be collected with great effort (Buenstorf & Schacht, 2013; Kani & Motohashi, 2012; Ruckman & McCarthy, 2017). However, this restriction does not hold for the intellectual property system in China. Since 2008 the China National Intellectual Property Administration (CNIPA, former SIPO) has endorsed a formal registration of license agreements and discloses information on all registered agreements. CNIPA, however, does not match license agreements to patent data and they also do not provide user-friendly download options, which is why some researchers have spent considerable time collecting Chinese licensing data by hand (Seo & Sonn, 2019b). For the empirical part of this dissertation, I was able to make use of the novel Chinese online platform IncoPat (www.incopat.com) that matches patent and licensing data, enabling me to work with (more or less cleaned) license and patent documents.[8]

I collected all licensed Chinese patents (granted invention patents and utility models, not design patents) with license commencement dates between 2000 and 2020 from IncoPat. Next, I used the OECD ENV-TECH classification (Haščič & Migotto, 2015) to identify environment-related technologies, which is the standard approach in this strand of research (Barbieri, Perruchas, & Consoli, 2020; Kemp et al., 2019; Perruchas, Consoli, & Barbieri, 2020). The ENV-TECH classification links patent classes (IPC and CPC) to eight environment-related technological domains, 36 subgroups and 95 technologies.

For data cleaning purposes, I used different text-based approaches to identify relevant information from the legal descriptions of all licensing agreements (in Chinese) such as applicant information, contract exclusivity or licensing commencement dates, among other things. A more demanding step needed for the analysis of spatial innovation diffusion, however, was the geocoding of licensor and licensee addresses using automated web-search queries in the application programming interfaces of Google Maps and Baidu Maps. I describe this process in more detail in section 4.3. A visualization of the entire data processing approach is provided in Figure A.4 in Appendix B. For the empirical analyses in chapters three, four and five, I work with subsets of this data set and additional data such as environmental indicators and socio-economic data. It is worth noting that this dissertation is one of the first attempts to use (Chinese) patent licensing data to study innovation diffusion.

In order to pursue research objective two, i.e. analyzing the spatial diffusion of environmental innovations, I used different quantitative approaches. Firstly, for chapter three, I made use of modern data visualization techniques to uncover the geography of licensing agreements. I developed a heat map that allows a better interpretation of network data, particularly for networks with many loops when compared to traditional network visualizations. The heat map highlights the fact that most green technology license agreements are concluded within the same region. Secondly, for chapter four, I used exponential random graph models (ERGM) to study

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[8] I am grateful for the recommendation of this database during a round table discussion with the research group of Gang Zeng at ECNU in Shanghai.

the determinants of inter-regional innovation diffusion. ERGMs are a class of statistical models that are particularly useful for the analysis of network data, since they can account for dependencies in network structures. They can predict the presence and absence of a link between any two nodes in a network from given network configurations, i.e. network characteristics on the node and tie level as well as structural network properties (Lusher, Koskinen, & Robins, 2013). ERGMs, despite the computational effort required, are a helpful method to study network structures and formations, offering great potential for quantitative research in economic geography (Broekel, Balland, Burger, & van Oort, 2014). Thirdly, for chapter five, my co-authors and I employed survival modeling techniques to study the speed of diffusion. More formally, we used accelerated failure time models to study which (regional) factors contribute to an acceleration or deceleration of the time-to-adoption in the diffusion process. Please note that although I use the term innovation diffusion throughout the dissertation, I do not describe the entire diffusion process in Rogers' sense (Rogers, 1962). I focus instead on the early diffusion phase.

A literature review addresses the final research objective of this dissertation, which is to critically appraise the role of regional determinants for environmental innovation development and diffusion. Together with my co-authors, we developed a so-called integrative (i.e. critical) review, which is especially suitable for emerging fields of research such as our case (Snyder, 2019). We analyzed several (empirical) articles that study the determinants of environmental innovation, filtering those articles that focus on regional factors or have explicit implications for regional studies. Based on these findings, we put together an agenda for future research on the geography of environmental innovation.

In summary, the research in this dissertation draws on a broad spectrum of methodologies ranging from a literature review and a qualitative case study approach to quantitative approaches rooted in graph theory and econometrics.

1.5 Overview of research projects

1.5.1 Accompanying articles

This short section provides an overview of research projects that are related to this dissertation but not included as distinct chapters. All projects listed below have (in)directly influenced the research included in this dissertation. The section is written with personal reflections and, in contrast to the rest of the dissertation, does not conform to the typical norms of academic writing.

Prior to this dissertation, two publications were prepared that deal with the Chinese innovation system. These articles discuss the notion of 'indigenous innovation', which constitutes the current innovation paradigm of the People's Republic of China. Ingo Liefner and I show that firms react very differently to the government’s call for ‘indigenous innovation’, with some firms engaging in high-tech products and others focusing on incremental product developments for low-cost markets (Liefner & Losacker, 2020). Firms also pursue different innovation strategies, with the majority of firms following an open innovation strategy based on science and technology-driven collaborations with extra-regional research partners, while others collaborate with a few well-trusted partners in their local environment (Losacker & Liefner, 2020a). The work behind both papers has greatly contributed to my understanding and knowledge of innovation processes in China.

Writing a dissertation obviously requires a lot of reading. While most of the relevant literature for the research in this dissertation comes from journal articles in the fields of economic geography, innovation studies, sustainability transitions and environmental economics, I have sought to familiarize myself with literature from other fields such as regional planning and political science in order to gain a broader perspective on the research topic. Two of these cross-disciplinary reading expeditions resulted in book reviews published in international journals. In Losacker (2021a), I discuss a political science view of China’s increasing responsibility in international climate policy by Kopra (2018). In Losacker (2021b), I review the great work by Fitzgerald (2020) on urban leadership for climate change, dealing with the idea of leading cities that pioneer in sustainable city planning. The critical review of these books has influenced the manner of thinking concerning this dissertation project.

One of the most enjoyable research experiences during the time spent preparing my dissertation was with my dear friend Sarah Karic, working on green urban planning

(Karic & Losacker, 2021). In our research project, we analyzed eight small and medium-sized cities in Germany hosting a so-called 'Landesgartenschau'. We discuss different acceleration mechanisms that amplify green projects and local sustainability initiatives. This research project on grassroots initiatives provided a stark contrast to the top-down and technology-driven green pathway in the Chinese context.

Another research project in addition to this dissertation involved cooperation with my colleagues Anne Otto and Lars Mewes. We used social sequence analysis techniques to map the evolution of industrial relatedness and complexity in 401 German regions over some 25 years. The project has helped me to uncover the wide scope of methodologies available for the study of regional dynamics and has thus indirectly contributed to the dissertation at hand.

Rainer Mehren, Janis Fögele, Lasse Jakobs, Ingo Liefner and I are also working together on a project that seeks to teach teachers. We organized three workshops for all geography teachers in the German state of Hesse who are responsible for the professional training of future geography teachers in the state. Due to these multiplier effects, the project will be of great importance for the future generation of geography teachers. The workshops aimed to transfer scientific knowledge about the Chinese innovation system and sustainability to school curricula, helping teachers to update their course contents. In the wake of the great societal challenges, I believe that geographers will be crucial for navigating societies towards more sustainable modes of living. However, this task requires high-quality education of future geographers in schools and universities, with this project being a small piece of the puzzle.

One further publication needs to be emphasized in this overview. In cooperation with Ingo Liefner and Balkrishna Rao, I published a short research note in Nature Sustainability (see Liefner, Losacker, & Rao, 2020). We argue that frugal design principles have great potential to reduce resource use in the production and processing of goods, eventually contributing to global sustainability. However, transition costs hamper the upscaling of frugal design principles, which leads to market failures. We suggest that policy intervention is needed to unleash the environmental benefits of frugality, for instance via mission-oriented policies and public procurement or via the integration of frugal thinking in engineering and management curricula.

Finally, Hendrik Hansmeier and I argue in favor of a combination of place-based supply-side and demand-side eco-innovation policies to enable regional sustainability transitions and foster regional lead market potentials (see Hansmeier & Losacker, 2021). This short paper is the result of many fruitful discussions we had on how to achieve sustainable regional development. We bring together common ideas from our research on the geography of environmental innovation and sustainability transitions, also including the notion of regional lead markets proposed in this dissertation. To those readers who may find value in this dissertation, I recommend waiting for the publication of Hendrik Hansmeier's dissertation in the near future, which will certainly provide many additional lessons.

1.5.2 Articles included

This dissertation includes a collection of five articles that have either already been published or are in the publication process with international peer-reviewed academic journals. Table 1 provides an overview of these articles, listing title and author(s), objectives, methods and publication status.

Table 1: Overview of articles in this dissertation

Title and author(s)	Objective	Methods	Publication status
Regional Lead Markets for Environmental Innovations *- Losacker, Liefner*	Developing a conceptual framework for the study of the geography of environmental innovation diffusion processes	Case study on waste management in Shanghai using interview, document and patent data	Published in *Environmental Innovation and Societal Transitions*
The Geography of Green Technology Licensing in China *- Losacker*	Revealing the prevalence of intra-regional innovation diffusion and local market formations	Data visualization using patent licensing data	Published in *Regional Studies, Regional Science*
‘License to Green’: Regional Patent Licensing Networks and Green Technology Diffusion in China *- Losacker*	Studying the patterns and determinants of inter-regional green technology diffusion	Exponential random graph models for regionalized patent licensing data	Published in *Technological Forecasting & Social Change*
Geography and the Speed of Green Technology Diffusion *- Losacker, Horbach, Liefner*	Studying the speed of green technology adoption and its (geographical) determinants	Survival models for time-to-adoption of patent licenses	Under review in *Industry and Innovation*
The Geography of Environmental Innovation: A Critical Review and Agenda for Future Research *- Losacker, Hansmeier, Horbach, Liefner*	Reviewing the literature on regional determinants of environmental innovations and setting an agenda for future research	Critical literature review	Under review in *Regional Studies*

The first article on regional lead markets for environmental innovations addresses research objective one raised in section 1.2.4, which involves developing a regionalized framework for the analysis of the spatial diffusion of environmental innovations. In this article, we develop a regionalized framework ('regional lead markets (RLM)') that can be used to study regional transition and innovation diffusion processes. We argue that regional lead markets are determined by regulatory advantages, demand advantages and technological advantages. A regional lead market adopts a subsequently successful innovation at an early stage and gains competitive advantage in the respective industry, driving national and international diffusion. We demonstrate the framework's applicability by providing illustrative evidence on Shanghai's lead market potential for waste management. The article is co-authored with Ingo Liefner, who helped to develop the conceptual framework and analyze the case study findings. He also contributed in writing minor parts of the article.

The second, third and fourth articles respond to research objective two, i.e. analyzing the patterns and determinants of spatio-temporal environmental innovation diffusion processes in China. All three articles make use of the patent licensing data described in section 1.4 as an indicator for innovation diffusion. The second article is a short single-authored publication that originated as a spin-off from article three. In the article, I use heatmap techniques to visualize the geography of green technology license agreements in China. The article highlights the fact that most green license agreements are concluded within the same region, which is often neglected when studying diffusion processes from a network perspective. In article three, I study the contrasting cases, namely inter-regional diffusion processes, building on the concept of regional lead markets. I explore the regional patent licensing network using exponential random graph models, finding that geographic proximity is a major driver of inter-regional innovation diffusion. Moreover, network activity and network popularity effects imply that a small number of regions are responsible for the diffusion of green technologies in China. Article four is co-authored with Jens Horbach and Ingo Liefner, who both contributed to writing minor parts of the article and interpreting the empirical results. They also helped to develop the hypotheses. In the article, we shift the empirical focus from spatial patterns of innovation diffusion to the temporal dimension. We particularly focus on the speed of innovation diffusion, i.e. the time that elapses before a patent is licensed. We use survival models to study how geographic proximity between innovator (licensor) and adopter (licensee) as well as region-specific characteristics affect the time-to-adoption of green technologies. Most notably, we show that geographic proximity to the innovator is associated with an accelerated time-to-adoption. Moreover, regional green specialization has a significant accelerating effect in the case of intra-regional licensing, but only for the innovator's region in the case of inter-regional licensing.

Article five addresses the third and final research objective. In the article, we review the current state of research on regional determinants of environmental innovation, including both innovation emergence and diffusion. We identify factors that can explain why some regions have better conditions for environmental innovation than others. We explicitly focus on supply side-determinants, demand-side determinants as well as institutional and political factors from a regional perspective, extending the standard set of determinants that mostly relate to the innovator or the adopter and not to the regional context (Horbach, 2008, 2019). Drawing on the critical review, we develop an agenda for further research on the geography of environmental innovation. The agenda is designed for researchers from core geographic fields such as human or economic geography, regional studies and regional science, but it will also be helpful for geographically interested researchers from environmental economics, innovation studies or sustainability transitions, among other fields. The results of all articles will be discussed in more detail in the corresponding sections as well as in the conclusion of this dissertation in section 7.1.

Figure 2 provides a brief outline of the internal structure of this dissertation. The Figure shows how the three research objectives are related to the research process (top two panels). Furthermore, it reveals the role of the individual chapters in this context and the methodological approaches which the chapters follow (bottom two panels).

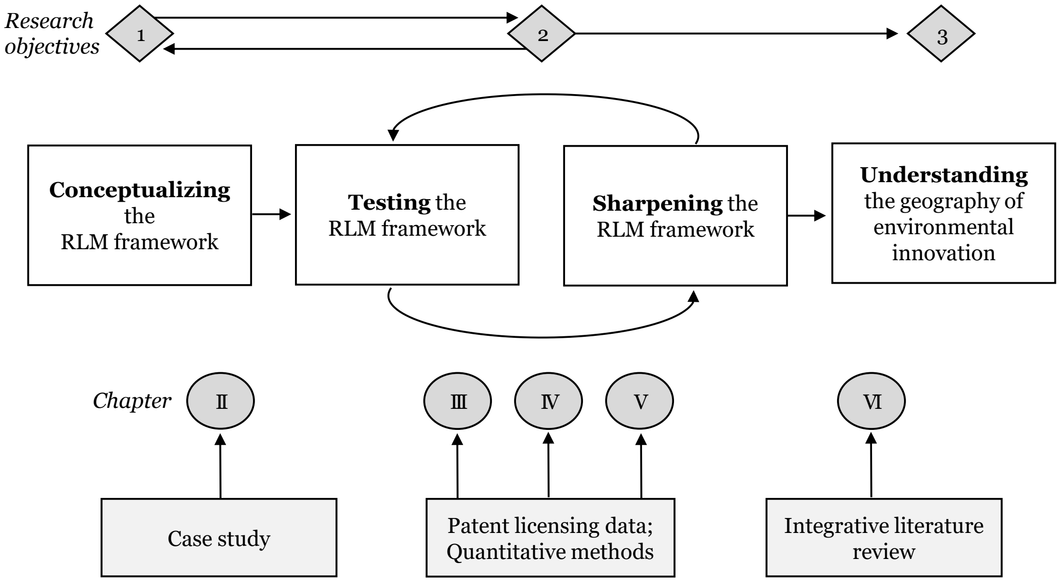

Figure 2: Internal structure and research processes in this dissertation

CHAPTER TWO

Regional Lead Markets for Environmental Innovation

Authors: Sebastian Losacker, Ingo Liefner

Status: This chapter is a preprint of a paper published in *Environmental Innovation and Societal Transitions* 37, 120-139.

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Abstract

The success of environmental innovations and sustainability transitions critically depends on market formations and diffusion processes. As of today, the geography of transitions literature provides suitable terms and case study evidence that these processes are highly regional phenomena. However, pertinent conceptual frameworks such as the multi-level perspective, technological innovation systems, or the somewhat less prominent lead market concept lack an explicit regional perspective. This paper develops a regionalized framework ('regional lead markets (RLM)') in order to provide a more appropriate conceptual lens for analyses of regional transition and innovation diffusion processes. We argue that regional lead markets are determined by regulatory advantages, demand advantages and technological advantages. A regional lead market adopts a later successful innovation at an early stage and gains competitive advantage in the respective industry, driving national and international diffusion. We demonstrate the concept's applicability by providing illustrative evidence on Shanghai's lead market potential for waste management.

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2.1 Introduction

A transition towards sustainable modes of production and consumption is needed to tackle global challenges such as climate change, resource depletion and environmental pollution (Köhler et al., 2019; Walz et al., 2017). In this context, environmental innovations are crucial to offer solutions for decarbonization, renewable energy generation, energy efficiency in buildings, waste management and so forth. In recent years, scholars have provided meaningful insights into the driving forces of how firms and research institutions engage in green technology research and how environmental innovations emerge (Hojnik & Ruzzier, 2016; Horbach, 2008). These innovation activities, however, are only worthwhile for society once environmental innovations are actually adopted on the market and diffuse globally. The literature on the geography of transitions offers a useful starting point to analyze the spatial diffusion of environmental innovation, as it is increasingly being emphasized that sustainability transitions are highly regional phenomena with pioneering regions leading global transition processes (T. Hansen & Coenen, 2015; Truffer & Coenen, 2012). However, conceptual frameworks mostly lack an explicit regional perspective, and much research focuses on case studies of regions that refer to non-regionalized frameworks such as lead markets, technological innovation systems or the multi-level perspective (Geels, 2011; Markard et al., 2015; Quitzow et al., 2014), leading to recent calls for more theoretical engagement on the geography of transitions (Binz et al., 2020). We hence observe a mismatch between that which has already been done in empirical research on regional transition and innovation diffusion processes and that which concepts and theories are in fact able to explain.

We propose that an explicitly regionalized concept can better serve as the theoretical foundation of regional transition analysis, as it draws attention to those factors that indeed matter on the regional scale. The aim of this paper is thus to close this gap and to provide a regionalized conceptual framework that is able to explain the early innovation adoption and (lead) market formation for environmental innovations. We adapt the well-established concept of lead markets for environmental innovation introduced by Beise and Rennings (2005), which argues that countries that adopt a later successful innovation at an early stage can act as lead markets, gaining competitive advantage, driving global innovation diffusion and setting technological standards. We do so by reframing original lead market factors from a regional perspective, focusing on both the demand and supply sides. Our adapted regionalized conceptualization relies on thorough literature work combining insights from innovation studies, economic geography and sustainability transitions. It is empirically informed by a novel database on environmental innovation, extensive desk research and expert interviews. The empirical illustration refers to Chinese regions, since China aims to take the leadership in global energy and sustainability transitions, based on a deliberate and strong regulatory push (Ely et al., 2019; L. Zhang, Sovacool, Ren, & Ely, 2017). This is also the reason why we frequently refer to literature that argues from a China-related background throughout the paper. We provide illustrative evidence on Shanghai's lead market potential for waste management, referring to the regionalized lead market factors. However, the framework is not intended to be China-specific, with the Chinese case simply offering useful properties from which to start.

The remainder of the paper is organized as follows. In section 2.2, we review the literature on the geography of sustainability transitions and market formations, motivating a more regional perspective. We briefly outline the original concept of lead markets for environmental innovation in section 2.3 and discuss the set of lead market factors that were found to be relevant on the national scale. Section 2.4 draws on insights from a seminal paper by Hansen and Coenen (2015) to establish which of the original lead market factors matter on the regional scale. We then develop a regionalized framework of lead markets for environmental innovation and discuss this adapted framework in detail. Section 2.5 provides illustrative evidence for the case of waste management in Shanghai, highlighting the applicability of the concept of regional lead markets. Section 2.6 discusses results and provides a conclusion.

2.2 Concepts of sustainability transitions: merits and shortcomings from a regional perspective

2.2.1 The geography of sustainability transitions

Sustainability transitions aim to understand transformations of industries and technologies driven by environmental issues and can be defined as '*long-term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption*' (Markard, Raven, & Truffer, 2012: 956). Studies on transitions predominantly refer to concepts such as technological innovation systems (TIS), the multi-level perspective (MLP) or lead markets. Table 2 compares these concepts in terms of their aims as well as their handling of innovation, competition and geography (Quitzow et al., 2014).

Table 2: Key differences between the lead market approach, the multi-level perspective and technological innovation systems
(adapted from Quitzow, Walz, and Köhler 2014)

Framework	Aim	Role of environmental innovation	Role of competition	Role of geography
Lead market (original version)	To explain the emergence and diffusion of global dominant designs	Highlights the special case of environmental innovations and the role of regulation in their diffusion	Focused on the interrelationship between country- and technology-specific competition with a focus on emerging technologies	Focused on the role of country-specific factors in shaping the competition between emerging technologies
Multi-level perspective	To analyze long-term technological change, i.e. shifts in technological regimes	Provides a framework for understanding transitions to more sustainable socio-technical regimes	Focus on the competition between different technological regimes	Not explicitly captured theoretically; Empirical studies mainly focus on single countries
Technological innovation systems	To analyze the dynamic development of emerging technologies	Suitable for the analysis of emergent environmental innovations	Not an explicit focus	Not captured theoretically; Empirical studies focused on single countries or comparisons

Recently, scholars have highlighted the importance of geography for studying sustainability transitions, as spatial contexts play a crucial role in understanding underlying dynamics and explaining heterogeneous developmental paths (T. Hansen & Coenen, 2015; Truffer & Coenen, 2012). The geography of transitions is, however, not about mapping transitions and claiming that transition processes affect places, but rather that transitions are spatially constituted (Bridge et al., 2013). In more detail, the regional perspective is crucial for analyzing transitions due to localized (informal) institutions such as shared values and norms (Wirth, Markard, Truffer, & Rohracher, 2013), technological and industrial specialization of regions, local resource endowments and regional policies (T. Hansen & Coenen, 2015). Considering these place-specific factors, shifting from a national lens to applying sub-national or regional perspectives on transitions is on current research agendas (Binz et al., 2020; Köhler et al., 2019). As a region can take a pioneering role, which can be followed by other regions and thus act as an accelerator for global transition processes, it is important to study leading regions and their impact on the spatial diffusion of environmental innovations (Cooke, 2011). Apart from that, there is a growing body of research in regional studies and economic geography exploring the emergence and diffusion of green technologies and green industries (Corradini, 2019; Essletzbichler, 2012; Grillitsch & Hansen, 2019; Strambach, 2017; van den Berge et al., 2020). Currently, however, empirical research cannot draw on theoretical frameworks which explicitly address the regional structures and dynamics of transitions and diffusion processes of environmental innovation. In fact, MLP, TIS and the original lead market model were not conceptualized for a regional perspective (Geels, 2011; Markard et al., 2015; Quitzow et al., 2014). This leads to a demand for more '*theoretical engagement*' in the geography of transitions community (Binz et al., 2020).

2.2.2 The geography of market formations

At the same time, Boon et al. (2019) have called for further research on market formation processes in sustainability transitions to explain the diffusion of (environmental) innovations. Dewald and Truffer (2011, 2012) offer fundamental lines of reasoning that emphasize spatial features of market formations. Firstly, the formation of market segments depends on geographical co-location of resources. Market segments, in this sense, incorporate actors, networks and institutional structures that lead to selling a specific innovation design. Secondly, the formation of market transactions between supply and demand sides is also affected by spatial contexts. For example, competition is driven by co-location of various suppliers, and commodifying follows a specific spatial logic. Thirdly, the formation of user profiles, referring to how end-users socially construct a product or an innovation design, is to some extent a spatial process. For instance, niche markets that are developed by end-users benefit from spatial proximity due to face-to-face meetings and supplier-customer interactions. These processes as well as the spatial outcomes and their determinants differ among different phases of market formation (Dewald & Truffer, 2012). The early phase of market formation in particular, the nurturing phase, is regionally constituted. As this early phase of market formation is crucial for global technology diffusion within the lead market concept, we argue for a regional perspective of lead markets. Also, we claim that regional lead markets are likely to play a key role in early market formation processes, in particular for the formation of market segments.

2.3 Lead markets for environmental innovation

2.3.1 Environmental innovation

Green technology development and environmental innovation are crucial to reduce global greenhouse gas emissions, mitigate climate change, prevent resource depletion and offer solutions for waste management. Moreover, innovation is the enabling factor driving transition processes. Studying environmental innovation, however, is different from regular innovation due to what is commonly referred to as the double-externality problem (Porter & van der Linde, 1995). From an innovation economics perspective, firms tend to under-invest in R&D, since innovation and knowledge can be understood as a partly public good with free-rider problems. However, first mover advantages, research funding and intellectual property protection reduce this effect. Investing in environmental innovation leads to a second externality because society as a whole benefits from the innovation's positive environmental impact, while the investing firm and the prospective adopters bear the costs. As a consequence, there is little incentive for firms to engage in R&D to develop environmental innovations (Rennings, 2000). Against this backdrop, traditional theorizing on technology push and demand pull factors (e.g. Pavitt 1984) is not sufficient to explain emergence and diffusion of environmental innovations and must be extended by a regulatory factor: the regulatory push/pull (Horbach, 2008; Rennings, 2000). The regulatory push/pull counteracts the double-externality problem and can be subsumed as policy intervention and government regulation (Beise & Rennings, 2005b; Rennings, 2000).[9]

2.3.2 Reviewing the original concept of lead markets

The concept of lead markets is used to study innovation diffusion.[10] It is argued that countries that adopt a later successful innovation at an early stage can act as lead markets, as these countries gain competitive advantage, drive global innovation

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[9] For a detailed overview of types of regulation from an innovation economics perspective see Blind (2012). Ren et al. (2018) provide examples for province level regulations in China.

[10] See Frenzel and Grupp (2009) for an overview of important frameworks for studying innovation diffusion.

diffusion, strengthen the dominant design and set technological standards. Countries that follow and adopt the lead-market-induced innovation design can be called lag markets (Beise, 2004). Globally dominant designs prevail on the market against competing innovations, often driven by early increasing returns to scale causing lock-in processes and standardization (Abernathy & Utterback, 1978; Murmann & Frenken, 2006).[11] Understanding how lead market dynamics evolve is hence crucial for the diffusion and adoption of environmental innovation and to guide sustainability transitions. Beise and Rennings (2005a) conceptualize lead market factors for environmental innovations, which, as discussed above, differ from regular innovations. The authors distinguish between five groups of advantages that constitute a lead market for environmental innovation: price advantage, transfer advantage, export advantage, regulatory advantage[12] and demand advantage (see Table 3). The original model by Beise (2004), however, did not include the regulatory advantage, as it is only relevant in the context of environmental innovation due to the double-externality problem (Beise & Rennings, 2005b). The regulatory advantage is based on the so-called porter-hypothesis (Porter & van der Linde, 1995) arguing that regulation can force firms to develop environmental innovations which, as a consequence, might also improve competitiveness. Following the logic that natural resources and energy have a market price, which is dependent on international environmental policy, the double-externality problem takes effect and hampers innovation development and diffusion in pioneering markets. This is particularly important for pioneering markets with relatively low prices. Regulation and policy diffusion are thus needed to constitute a lead market for environmental innovation, hence attaching great importance to the regulatory advantage in the lead market model for environmental innovation (Beise and Rennings, 2005a). The regulatory advantage is even more important in the context of infrastructure-related innovations (e.g. in the energy system). Next to the double-externality problem, environmental infrastructure innovations are exposed to another challenge: monopolistic bottlenecks. This is due to the quasi-monopolistic market conditions of actors in infrastructure systems and leads to a triple regulatory challenge (Walz, 2007).

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[11] The applicability of the dominant design concept in the lead market framework is controversial. This is due, for instance, to different types of innovation under investigation (e.g. infrastructure-related innovations vs. simple consumer goods). We refer to Quitzow et al. (2014) for a critical assessment of the concept of dominant designs in the lead market literature. The notion of dominant designs should thus be treated with caution and should not be interpreted too narrowly.

[12] Note that the term regulatory advantage is commonly used in the literature even though Beise and Rennings (2005a) originally referred to the factor as the porter effect.

Table 3: Lead market factors for environmental innovation (adapted from Beise and Rennings 2005; Quitzow, Walz, and Köhler 2014; Beise 2004)

Lead market factor	Description
price advantage	The price advantage stems from country-specific conditions leading to relatively low costs for the nationally preferred innovation design. Market size and growth can induce such a price advantage due to economies of scale. The price advantage is theoretically grounded on the globalization hypotheses by Levitt (1983) claiming that consumers in foreign countries abandon their preferred innovation design and adopt the relatively cheaper design from the lead market country.
transfer advantage	Transfer advantages are to be understood as country-specific conditions that induce demonstration and bandwagon effects for an innovation design (see Mansfield 1968) Other countries perceive a lower level of risk for the adoption of an innovation design once the lead market proves the innovation's benefit.
export advantage	Export advantages are based on the inclusion of foreign demand preferences in the innovation design adopted by the lead market. The export advantage follows three main mechanisms. Firstly, domestic demand is close to needs of foreign countries. Secondly, domestic firms are experienced in exports. Thirdly, national market conditions are similar to foreign market conditions in terms of socio-cultural as well as economic properties (see Vernon 1979).
regulatory advantage	The regulatory advantage is based on porter's hypothesis (Porter & van der Linde, 1995) that effective regulation and policy can trigger firms to innovate in green technologies which enhances their competitiveness. Given the fact that natural resources and energy have a market price that depends on international environmental policy and regulations, market structure advantages (i.e. high competition) are not effective whatsoever. Hence, regulation and environmental policy can substitute this effect.
demand advantage	A demand advantage corresponds to national conditions that increase the demand for an innovation and that emerge over time in other countries as well. Demand advantages arise from country-specific demand conditions (e.g. risk of flooding, new modes of transportation). Lag markets anticipate the benefits of the innovation designs first adopted in the lead market.
technological advantage	Technological advantages are supply-side factors that favor lead market development. The advantage is based on the notion that innovation adoption is strongly affected by technological capabilities. Here, user-producer interactions, feedback loops and regional innovation system rationales are crucial.

The original notion of lead markets (Beise, 2004; Beise & Rennings, 2005b) refrains from incorporating supply-side factors. Recently, however, literature has emphasized the importance of supply-side factors such as technological capabilities for constituting lead markets (Horbach et al., 2014; Lacerda & Van den Bergh, 2014; Quitzow et al., 2014; Tiwari & Herstatt, 2012). This fits with the arguments put forward by Coenen, Benneworth, and Truffer (2012) that concepts in transition studies need to further acknowledge local and global facets of innovation systems, hence considering supply-side factors. Further reasoning for considering the supply side in the lead market concept is mainly based on the following points: (1) evolutionary theory of trade, claiming that trade performance is dependent on technological capabilities, (2) the embeddedness of technologies in different industry clusters, (3) user-producer interactions, which facilitate learning and knowledge flows (Quitzow et al., 2014).

Therefore, the original lead market model needs to be extended by a technological advantage.[13] This is closely linked to the importance of existing capable actors and networks as well as complementary sectors on the supply side. On the one hand, capable actors are required to guide innovations out of a niche, while on the other hand, the strength of complementary sectors is known to affect the success of the technology or industry under investigation (Fagerberg, 1996; Walz & Köhler, 2014). The lead market concept, though mostly used to study innovation diffusion, can also contribute to the wider debate on regime shifts within sustainability transitions (Walz & Köhler, 2014). Moreover, the notion of lead markets is widely used in national and international policy making (e.g. in Germany, see Walz et al. 2019 or the EU, see Edler et al. 2009b). In innovation policy, the concept is a useful means to increase the competitiveness of an industry by establishing a large domestic market with early mover advantages for domestic firms (e.g. learning, patent protection, etc.). This is mainly due to the concept's demand-orientation, since a focus only on technological leadership and R&D cannot guarantee long-term competitive advantages in an industry or technology (Meyer-Krahmer, 2004).[14]

2.4 Regionalizing lead market factors

The notion of lead markets was originally developed as a country-level framework to explain global innovation diffusion (Beise, 2004). Despite its national focus, Quitzow, Walz, and Köhler (2014) highlight the advantage of a lead market perspective when analyzing the geography of transitions. We argue, however, that the role of geography, and in particular sub-national regions, is still vague in the current scholarly discussion on lead markets (for an exceptional case, see Karakaya et al. 2014). This is mainly due to presupposing that lead markets must be countries. In the following section, we suggest a regional perspective on the above-mentioned lead market factors and refrain from the a priori assumption of lead markets being countries. Subsequently, we draw on a seminal paper by Hansen and Coenen (2015) to identify which regional lead market factors matter in the light of place specificity in sustainability transitions. As a

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[13] Henceforth, we refer to the technological advantage for denoting supply-side factors. For the purpose of the paper, this not only includes the technological capabilities per se, but also actor capability and the strength of complementary sectors (see Walz and Köhler, 2014).

[14] For a detailed discussion on lead markets as an innovation policy tool, see chapter three in Quitzow et al. (2014).

result, we provide a stylized model of regional lead markets for environmental innovation.

2.4.1 Lead market factors revisited

(1) Price advantage: The price advantage is determined by specific conditions that lead to relatively low costs for an innovation such as economies of scale in large markets (Beise, 2004; Beise & Rennings, 2005b). On the country-level, the price advantage is strongly linked to currency rates, international trade, factor price changes and taxes. It can arise from both increasing or decreasing factor prices. For instance, due to the globally increasing abatement costs for pollution and environmental harms, countries and regions with the highest relative costs are likely to become lead markets for environmental innovation (Beise, 2004: 1003). In accordance with the literature on clusters, price advantages can also be achieved on the regional level through several factors such as regional subsidy programs, regional policies and agglomeration economies (Porter, 1998).

(2) Transfer advantage: The transfer advantage builds on demonstration and bandwagon effects (Beise, 2004). These, of course, can be countrywide demonstrations, but it is also pioneering regions that demonstrate benefits of an innovation design as well as new policies or regulations. So-called transition regions can act as lighthouses for environmental innovation and are subject to learning visits by other regional or national policy-makers (Cooke, 2011). Also, regions or cities are often used as an experimental field for testing (e.g. ‘tinkering’ in Chinese regions, see Heilmann et al., (2013)). This transfer advantage can be exploited first nationally and then globally. However, the demonstration effect of transition regions mainly takes effect within national boundaries, while it is demonstration effects on the country level that receive international attention (Beise, 2004; Cooke, 2011). In addition, the transfer advantage captures the international reputation of a country or region for a specific technology (Rennings & Smidt, 2010).

(3) Export advantage: The export advantage stems from three major factors (see Table 3). The first of these is the fact that domestic (regional) demand is close to the needs of foreign consumers. This, of course, differs across regions within one country. In China, for instance, coastal regions are more Western-oriented than inland China (Y. Zhou et al., 2016). This also holds true for most less developed or developing countries when comparing coastal to inland areas or city to peripheral regions in terms of similarity to

foreign consumer needs. Secondly, an export advantage arises from export experience of firms. Referring to China again, firms located in areas along the coast have more experience in exports due to the earlier economic opening. Also, regarding the third factor for export advantages, these regions' markets are closer to foreign market conditions both socio-culturally and economically (Wei & Liefner, 2012). Nonetheless, it is national trade agreements and further countrywide determinants that mainly constitute the export advantage.

(4) Regulatory advantage: The regulatory advantage is based on the double-externality problem for environmental innovations or on the triple regulatory challenge for infrastructure-related innovations respectively. Hence, regulation is needed to foster both environmental innovation emergence and adoption (Hojnik & Ruzzier, 2016; Rennings, 2000). Despite international and national regulations that seek to mitigate environmental pollution, greenhouse gas emissions and so forth, regulations can address region-specific problems, and can be provided and implemented on the regional scale (J. Chen, Cheng, & Dai, 2017; Hao, Deng, Lu, & Chen, 2018; Mi, Gang, Xin, Shang, & Hai, 2018). This is strongly linked to the demand factor as well as the technological factor. Popular examples for this phenomenon include regional pollutant emission measures, waste management laws or citywide bans for single-use plastic bags, forcing regions to adopt an environmentally friendly innovation (Shen, Wei, & Yang, 2017; Wu, Wei, Chen, & Yuan, 2019). The triple regulatory challenge for infrastructure innovations, namely the additional challenge of monopolistic bottlenecks, unfolds its spatial scope dependent on the specific innovation under study. For instance, grid access for actors in renewable energies might be regulated on the national level (Walz, 2007), while the monopolistic bottleneck for water management or public transport might be regulated on the regional level (e.g. city water treatment, streetcars, etc.). In this context, Edler and Georghiou (2007) highlight the importance of public procurement to address demand-side issues for innovation adoption and diffusion. As these procurements are often implemented regionally and follow tenders by regional authorities, the regulatory advantage for lead markets might differ among regions (Yanchao Li, 2011). In essence, the regulatory advantage is based on the idea of regulation and policy diffusion. A promising regulatory path pursued by a leading region can be followed by other regions and countries (Cooke, 2011).

(5) Demand advantage: Demand conditions can differ among regions. Taking the popular case on the risk of flooding as an example, it is obvious that demand in coastal

regions is higher than in mountainous inland areas. Also, it is metropolitan city-regions and industrial regions that increasingly suffer from air pollution (Shen et al., 2017; Wu et al., 2019). Therefore, we can observe large regional differences in the development of green buildings in China (Zou, Zhao, & Zhong, 2017). Metropolitan cities also require new modes of transportation to reduce air pollution and greenhouse gas emissions. In Shenzhen, for instance, this demand is strongly supported by the local government, implementing several regulatory measures and providing subsidies and public procurement for new energy vehicles (Lauer & Liefner, 2019). Demand, especially when it comes to environmental innovation, is often regional rather than country-specific. For the Chinese case, we can observe large regional differences in air quality (e.g. PM2.5 concentrations), freshwater quality (e.g. eutrophication rates), land use (e.g. biodiversity) and impacts of climate change (e.g. rising sea levels, desertification) (Ministry of Ecology and Environment (MEE), 2018a). The demand for pollution abatement technologies or water treatment technologies, for example, thus differs among regions. However, the spatial scope of demand for a specific innovation depends on the type and extent of the environmental problem.

(6) Technological advantage: The technological advantage is a supply-side factor that arises from technological capabilities of lead markets as well as strong complementary sectors and capable actors. These supply-side factors are increasingly emphasized in the literature, as it is crucial for lead markets not only to adopt innovation designs, but also to be technologically upfront (Quitzow et al., 2017, 2014). There is a long tradition in economic geography and innovation studies of highlighting the fact that technological capabilities and innovativeness are spatially concentrated and not evenly spread. Numerous frameworks allow for studying these regional innovation capabilities with an emphasis on the spatial context. For instance, clusters illustrate how spatial concentrations of interconnected firms and institutions in a specific field drive competitiveness and innovation capabilities (Porter, 1998). Regional innovation systems and related concepts explain how regions are crucial for transferring tacit knowledge, and how they benefit from localized institutions and norms, intraregional mobility of human capital and regional innovation policies (Cooke, 2001; Moulaert & Sekia, 2003). In both frameworks, regional value chains that incorporate regional supplier-customer relationships are crucial, as they cause knowledge spillovers and facilitate feedback loops in interactive innovation processes. These feedback loops lead to arguing that regional innovation adoption is strongly affected by regional innovation generation (Dewald & Truffer, 2011). Recently, scholars have argued that technological

capabilities and technological progress are both path and place-dependent due to regional industrial and technological specialization and diversification processes (Heimeriks & Boschma, 2014). For the Chinese case, innovation capabilities and technology development are mainly concentrated in three regions: the Pearl-River Delta, the Yangtze-River Delta and the Bohai Rim area (Kroll, 2016).

2.4.2 Place specificity in sustainability transitions vs. lead market factors

We can conclude so far from revisiting the lead market factors that all factors manifest their effects to a certain extent on a regional scale. In a pivotal paper, Hansen and Coenen (2015) collate five major themes on the place specificity in sustainability transitions, emphasizing the role of geography for studying transitions. These themes correspond with several lead market factors. Synthesizing place specificity themes and lead market factors hence allows the establishment of the spatiality of lead market factors in more detail. Acknowledging Hansen and Coenen's paper as a seminal work on the geography of sustainability transitions, we use this contribution to establish which lead market factors matter regionally, and which ones not. We thus respond to their call that '*Application of theories in new geographical settings generally implies that the theories need to be revised and further developed in a direction that is more sensitive to geography'* (p. 14). Table 4 provides the correspondence of themes and lead market factors. In brief, the regulatory and demand advantage shows strong correspondence to the place specificity themes of sustainability transitions, highlighting the regional dimension of these factors. The technological advantage, at least indirectly, features correspondences to all place-specific characteristics of sustainability transitions, which places emphasis on the proposition that this lead market factor in particular is highly regionally determined. In contrast, price, export and transfer advantage might vary within a country as outlined earlier, but do not explicitly correspond to the place specificity in sustainability transitions. We thus focus on the demand, regulatory and technological advantage for conceptualizing regional lead markets.

Table 4: Place specificity in sustainability transitions vs. lead market factors

(themes and implications adapted from Hansen and Coenen 2015)

Themes (Hansen & Coenen 2015)	Implications (Hansen & Coenen 2015)	Corresponding lead market factors*
Urban and regional visions and policies	• Urban and regional policies are central to facilitate the embedding and diffusion of niche technologies • Policy generally aims to combine ecological goals with economic competitiveness • Often, such policies also stimulate industrial development of cleantech industries • The governance of transitions encompasses multiple policy areas, thus they are contested and negotiated between multiple public, quasi-public and private territorial actors	regulatory advantage (technological advantage)
Informal localized institutions	• Development and diffusion of environmental innovations are conditioned by informal localized institutions • Niche formation is embedded in localized social practices • Informal localized institutions positively influence the regulatory push on the development and adoption of environmental regulation	(regulatory advantage) (technological advantage)
Local natural resource endowments	• Resource scarcity stimulates investments in renewable energy development and diffusion • Resource endowments influence choices between renewable technologies	demand advantage (technological advantage)
Local technological and industrial specialization	• Industrial specialization conditions the development of innovations necessary for sustainability transitions • The extent of knowledge spillovers in a region influences the ability of firms to develop environmental innovations • Local industrial specialization is often the outset for selective regional policy agendas, which in turn reinforce technological and industrial specializations	technological advantage
Consumers and local market formation	• Engaged local end-users are central to local market creation • Geographical proximity enables producers to obtain feedback from end-users for emergent niche technologies	(demand advantage) (technological advantage)

* Lead market factors with weak correspondences in parentheses.

2.4.3 A conceptual framework of regional lead markets for environmental innovation

Based on the arguments discussed above, Figure 3 outlines the building blocks for a conceptual framework of regional lead markets for environmental innovation (RLM). The framework follows the original model of how lead markets induce innovation diffusion as illustrated by Beise and Rennings (2005a). It shall serve as a heuristic to study the diffusion of environmental innovation from a regional perspective. On the one hand, the framework allows an analysis of lead markets on the regional level, while on the other hand, it can be used to study the regional dimension of lead market factors for country-level settings. The RLM framework is not intended to argue for a strict regional lens for studying innovation diffusion, but rather serves to complement the original lead market concept with more sensitivity for space and scales. The question of whether a lead market for a specific innovation is regional or national, depends on the empirical context.

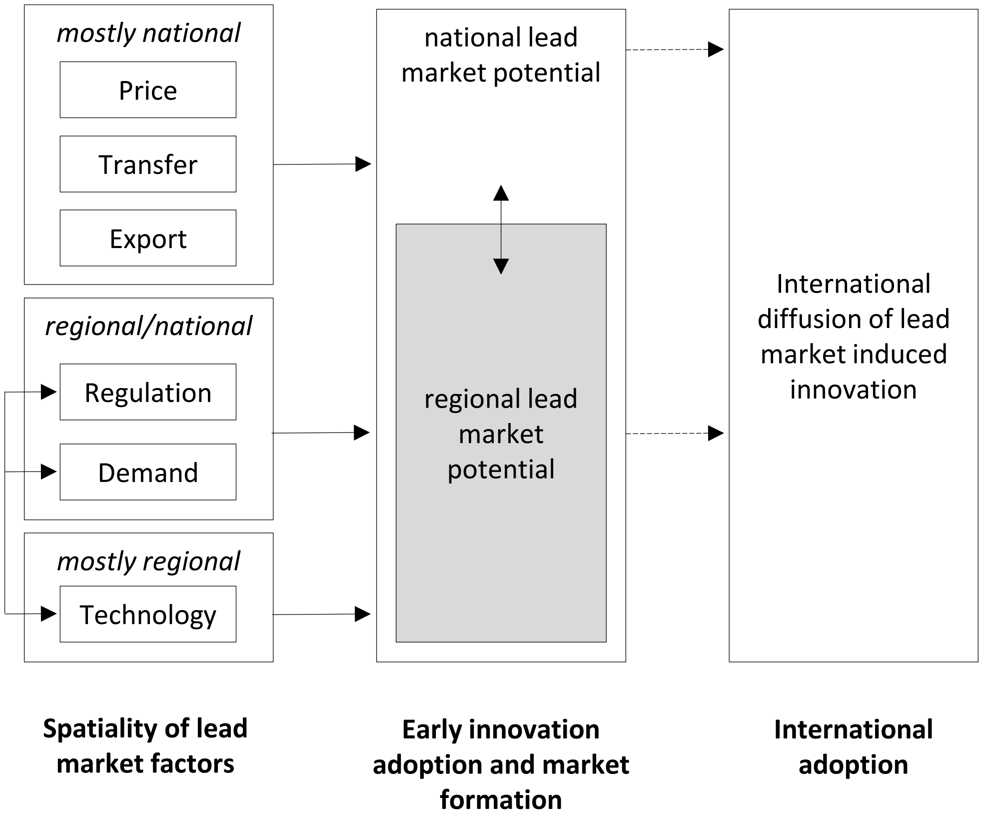

Figure 3: Conceptual framework of regional lead markets for environmental innovation

In a first pillar, the varying spatiality of lead market factors is depicted. As argued above, all factors are to a certain extent regionally constituted. However, based on the review of all factors and the discussion of the place specificity, we assume the price advantage, transfer advantage and export advantage to mostly take effect on the national level and follow the original reasoning by Beise (2004). In contrast, the regulatory advantage as well as the demand advantage are assumed to be often constituted on the regional level, while the technological advantage should be considered the most region-specific lead market factor. The spatiality of lead market factors as depicted here, however, is to be understood as an initial guideline and is likely to vary according to the empirical case under study.

Next, it is important to emphasize the interrelation of different lead market factors in a regional context. That is to say, the technological advantage bears important linkages to both the demand and regulatory factors (Quitzow et al., 2014). This is a crucial building block for a regionalized framework, as the regional technological advantage, which marks the supply-side dynamics, induces regional demand and vice versa (T. Hansen & Coenen, 2015; Liao, Xu, Cheng, & Dong, 2018). Also, the interconnection of regional demand and technological advantage is crucial for market formation processes (Dewald & Truffer, 2012). Feedback loops between regional supply and demand cause both a reinforcement of each advantage as well as a co-emergence of both factors (Porter, 1998). Therefore, it is likely that a demand advantage and a technological advantage form in the same region. In addition, regional regulatory advantages such as city or province-wide policies and directives affect and guide both regional demand and the technological advantage of regions. For instance, Wu et al. (2019) find that regional environmental regulation measures such as pollutant emission controls strongly affect the industrial structure of China's Yangtze River Delta. Shen et al. (2017) find empirical evidence that emission reduction policies have pushed heavy industry from the Pearl River Delta to more peripheral regions. Also, public procurement as a regulatory tool directly affects regional demand (Edler & Georghiou, 2007; Lauer & Liefner, 2019). On the other hand, supply-side factors determine regional policies and regulations under a place-based policy logic (Tödtling & Trippl, 2005). Hence, regulation, demand and technological advantage in a region are strongly interrelated, causing feedback loops and reinforcing effects. This suggests that the three factors co-emerge in the same region, eventually creating a regional lead market for a specific innovation.

As illustrated in the second pillar of Figure 3, the regional lead market potential is interconnected with and embedded in the countrywide lead market potential. The early innovation adoption as well as market formation processes can take place in the regional lead market and might lead to the national and international adoption of the environmental innovation, hence resulting in the global diffusion of an innovation induced by the regional lead market. This also captures the idea that a country's lead market position might be established on the national level, while several regions within that country contribute differently to the lead market factors. Therefore, lead markets can be established on a regional or on a national level, depending on the spatiality of the lead market factors in a specific empirical setting. The regional dimension of the regulatory advantage might play an important role in this regard, as niche experience can foster policy learning (Boon & Bakker, 2016; Heilmann et al., 2013). This implies that regional experience can affect national regulations, which in turn reinforces (regional) lead market formation. In order to summarize the notion of regional lead markets, we adapt the original definition by Beise and Rennings (2005b) as follows:

Regional lead markets (RLM) for environmental innovation are sub-national regions with large markets that adopt a later successful innovation at an early stage and gain competitive advantage in the respective industry. They can drive national and international diffusion processes and global standardization. RLMs might emerge in specific empirical contexts where the national lead market framework is less applicable, as important lead market factors are constituted on the regional level.

For the empirical analysis of regional lead markets, some differences to original lead market studies need to be considered. That is, the lead market factors differ in empirical measurability at the regional level. Price, transfer and export advantages are difficult and vague to measure quantitatively at the regional level. On the other hand, indicators for the regulatory, demand and technological advantages can be established on different spatial scales relatively easily in terms of data availability and relatively accurately in terms of construct validity. We outline common indicators for all lead market factors in Table 5 to support this argument.

Table 5: Commonly used quantitative indicators for lead market factors and their availability on the regional level

Lead market factor	Common quantitative indicators	Data quality and availability on the regional level	Explanation and sources
price advantage	purchasing power parities, labour costs, resource endowments, absolute or comparative cost advantages, large firms	Inaccurate	Data is only easily available for countries (e.g. World Bank, OECD, Eurostat, etc.) and it is difficult to obtain regional data.
transfer advantage	patent statistics, product efficiency, reputation, demonstration projects	Inaccurate	Data can be gathered for the regional level (esp. patents and demonstration projects). In general, however, most indicators for the transfer advantage are rather vague.
export advantage	Export-important ratios, balance of trade, firms' export experience, market structure and conditions	Inaccurate	Export and trade data (e.g. via UN Comtrade) is easily available on the country level. For regions there is no such secondary data. Also, it is difficult to assess the similarity of market conditions between regions.
regulatory advantage	standards, eco-labels, regulations, Feed-in tariffs, taxes, emission trading systems, laws, procurement	Accurate	Data for regulatory measures is publicly available from government websites or policy documents and provides detailed information on the spatial scope of application.
demand advantage	market size, per capita income, awareness for sustainability issues, special needs for environmental innovation (e.g. high air pollution)	Accurate	All indicators for demand can be easily obtained on the regional level (open administrative data, statistical offices)
technological advantage	patent shares, patent counts, relative patent advantages, skilled workers, leading firms	Accurate	All indicators for technological advantages can be easily obtained on the regional level (e.g. REGPAT, PATSTAT, statistical offices)

Indicator sources: Beise and Rennings, 2005b, 2005a; Cleff and Rennings, 2016; Horbach et al., 2014; Jacob et al., 2005; Karakaya et al., 2014; Lacerda and Van den Bergh, 2014; Rennings and Smidt, 2010; Walz and Köhler, 2014

Note: Due to the broad definition of environmental innovation in this paper, the list of indicators is not intended to be complete and some indicators might not be useful for specific types of innovation. For instance, indicators for lead market factors for infrastructure-related innovations (e.g. energy supply) differ from eco-efficiency innovations (e.g. low material use) and large-scale innovations (e.g. waste incineration plants) differ from consumer goods (e.g. residential rooftop PV systems). Thus, the choice of indicators depends on the innovation under study. Walz and Köhler (2014) discuss indicators for lead market factors in relation to availability for different innovations, availability over time, robustness, and their relation to the multi-level perspective. This table serves to complement their findings.

2.5 Demonstrating the applicability of the RLM concept: The case of waste management in Shanghai

In order to demonstrate the applicability of the RLM concept, the following sections provide insights from a case study on waste management technologies in Shanghai. The section is organized as follows. Firstly, we discuss China's role in sustainability transitions on a general level and explain the importance of regions for the analysis of transition processes in China. Secondly, we outline our empirical approach and provide details on methods and case study design. Thirdly, we condense the most important information on the case and explain recent developments. Finally, we analyze the three relevant RLM factors: regulation, demand and technology.

2.5.1 China's role in sustainability transitions

China is assumed to be of key importance for future environmental innovation and green technology development (Ely et al., 2019; Walz et al., 2017). At present, China is among the leading countries in green technology patenting (according to WIPO and GreenTechDB) and is considered to play a major role in niche formation, replacing its old strategy of catching up and leapfrogging (Binz et al., 2012; Gosens, Binz, & Lema, 2020). In this respect, China's central and regional governments have strong regulatory and financial power for intervening in the market and thus exhibit huge potential to steer environmental innovation emergence and diffusion, as both critically depend on adequate implementation of innovation policies (Veugelers, 2012). For instance, enhancing innovation demand in a mission-oriented way offers potential to guide transition processes (Boon & Edler, 2018; Mazzucato, 2018). This mission-orientation has been put into practice in China's current political paradigms: China's *13th Five-Year Plan* highlights the importance of tackling climate change and further environmental problems with green technologies. Furthermore, place-based innovation policies are widely recognized to improve regional innovation capabilities and to facilitate both innovation development and innovation diffusion (Tödtling & Trippl, 2005). Following a logic of 'tinkering', policymakers in China often establish model regions for testing new regional policies (Heilmann et al., 2013). Public procurement instruments are also increasingly employed to drive demand and promote innovation adoption, guiding future technological trajectories (Edler &

Georghiou, 2007). The importance of central and especially local governments in the Chinese economy offers great potential for innovation diffusion and lead market creation driven by public demand (Edler, Corvers, et al., 2009; Yanchao Li, 2011).
The interplay of China's policy-driven approach towards innovation and its hugely varying regional innovation potential becomes evident from many studies that analyze innovation in China from a regional perspective (Losacker & Liefner, 2020a; Wei & Liefner, 2012). China is characterized by high levels of spatial disparities regarding well-being and income, economic structures and growth potential, endowments with S&T and R&D resources, and innovation-related mindsets (Huggins et al., 2014; J. Wang et al., 2019). Hence, a national perspective on lead markets is of relatively limited explanatory power, since national averages blur real structures, and existing hot spots of innovative potential are systematically overlooked (Liefner & Kroll, 2019).

2.5.2 Methods and case study design

Based on the arguments discussed above, we believe that the case of waste management in Shanghai marks a suitable example to illustrate how the regional lead market concept for environmental innovation can be applied. The case study involves three major elements that in combination ensure a high validity of our findings (Yin, 2017): (1) expert interviews and on-site visits, (2) extensive desk research and (3) quantitative patent analyses (see Appendix A for a more detailed description of methods). Firstly, we conducted semi-structured expert interviews with senior executives and project managers from the world's biggest waste incineration plant in Shanghai. Involving both executive-level personnel and project managers conforms to a multiple informant approach and avoids undetected informant biases. We also interviewed high-ranking scientific advisors to waste management projects of the Shanghai municipal government as well as regional government officials. Since the advisors helped to develop Shanghai's waste management strategy and to organize its operational management, they could contribute the experts' perspective, increasing the case study's internal validity. In order to assess the significance of the case examined in Shanghai, we visited and consulted representatives of two waste incineration plants in Germany before the field work in Shanghai was carried out. Altogether, we conducted twelve expert interviews between October 2018 and October 2019. Nine interviews lasted approximately one hour, while three interviews were combined with on-site visits of incineration plants and lasted about four hours. We analyzed the written records and documentation using a qualitative content analysis approach. Following a strategy of theoretical saturation, we have limited the number of expert interviews.

Secondly, the case study relies on extensive desk research for triangulation purposes and to further deepen our understanding of waste sorting and utilization processes. The desk research includes, among other documents, technical reports on waste incineration plants, scientific studies, government documents, newspaper articles and information from companies, many of them in Chinese.[15]

Thirdly, in order to complement the qualitative information established from interviews and document analysis with quantitative information, and in order to place the case study in the broader technological field, we carried out a patent analysis of waste-related technologies with novel data retrieved from GreenTechDB (Perruchas et al., 2020). The database lists patent families from 1970 to 2010 extracted from PATSTAT. It utilizes the OECD ENV-TECH classification system for identifying environment-related technology patents and offers geolocation of inventors down to county/city levels (see Appendix A for a detailed description of this data source as well as further information on ENV-TECH). The patent analysis also includes regional technological specialization numbers by employing the Relative Patent Activity (RPA) (e.g. Köhler et al., 2014). Altogether, we gathered a comprehensive and multi-faceted range of material, which provides valid and reliable information concerning the factors that are part of the RLM concept. Analyzing three different types of data further ensured methodological triangulation.

2.5.3 Waste management in Shanghai

According to World Bank data, the amount of global waste generation is expected to increase drastically until 2050. With most (developing and developed) countries still making use of (open) landfills, a global shift towards more sustainable modes of waste management is needed. As waste incineration plants create win-win situations, firstly by offering a disposal solution with low-environmental impacts, and secondly by producing energy, global expansion of such plants is sought (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018). Incineration is a process of waste management that uses thermal treatment to generate energy from waste. Large incinerators in particular are crucial

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[15] Documents in Chinese were searched for by research assistants or Chinese colleagues and were translated either by them or using software.

for both waste management and energy production due to their higher efficiency. Accordingly, incineration is regarded as a key factor in sustainable waste management (Brunner & Rechberger, 2015; Lombardi, Carnevale, & Corti, 2015). In recent years, China has reacted substantially to the national and international challenges concerning waste disposal and pollution. For instance, China's National Sword policy regulates the import of foreign waste, and the current 5-year plan (2016-2020) explicitly calls for improved waste management and progress in the implementation of a circular economy. Understanding and forecasting the global diffusion of waste management innovations is an important ingredient of sustainability transitions that serves well to demonstrate the applicability of the regional lead market concept.

On 1 July 2019, the region we examine in this paper, Shanghai, passed a new law that regulates the systematic sorting of waste in order to increase recycling rates, mitigate pollution and improve energy production from waste incineration. In addition, Shanghai Chengtou Group, owned by Shanghai Municipal Government, set up the world's largest waste incinerator in Pudong, Shanghai. This plant, due to the regulation of waste sorting, is now able to produce 600 kWh per ton of waste (dry waste), while the performance before the implementation of the sorting system was considerably lower (400-450 kWh per ton of waste (mixed waste)). This level of energy production meets global top-tier technology standards. However, the incinerator's size in terms of treated waste is significantly larger and more energy-efficient than that of (Western) competitors, and emissions are also noticeably lower, qualifying the plant's innovative nature. In particular, the emissions of dust, acid and other gases (e.g. HCl, SO_2, NO_x), heavy metals, carbon monoxide, dioxins and furans from the plant into the air comply not only with high environmental standards and regulations (e.g. Directive 2010/75/EU) but also with the level of best available technologies (see Table A.1 in Appendix A for more details). The incinerator treats approximately 3,285,000 tons of dry residual waste per year, which sets a global record, while regular-sized plants mostly do not exceed 500,000 tons. This leads to potential power generation for 1,300,000 Shanghai residents, according to the executives' statements.

The incineration plant can thus be considered a multi-faceted environmental innovation combining technological as well as organizational elements. In fact, one representative explained that *'the plant is not only technologically state-of-the-art, but also has the unique feature that the enormous size of the plant and the scaling can be managed organizationally and logistically without compromising energy efficiency and environmental performance'* (authors' translation from interview

I.SIP.2). As it is an infrastructure-related innovation, it shares characteristics of other infrastructure regimes such as monopolistic bottlenecks and a long lifetime (see Walz and Köhler, 2014). Being the first city in China to introduce the sophisticated sorting system and to establish high-technology garbage incinerators, Shanghai has the potential to become a regional lead market for waste management, eventually affecting national and global diffusion and setting standards in the industry. The prospective diffusion is reflected in regional plans for waste management. For instance, Yunnan intends to build 46 new incineration plants, while Henan aims to construct 75 plants by 2030 according to the provinces' strategic plans.[16] As these projects are to be implemented through public-private-partnerships, competition among several actors and regions is high (Yun Li, Zhao, Li, & Li, 2015). Considerable effort has been made by the local government and the operating companies involved in Shanghai's waste management in order to build a positive public image and demonstrate Shanghai's leading position in the industry. The experts also explained that government authorities from various Chinese regions are interested in copying the Shanghai model of waste management and frequently visit the plant and engage in negotiations. This clearly indicates early innovation diffusion processes.

2.5.4 Lead market factors

Three regional lead market factors are important to constitute Shanghai's lead market potential for waste management innovations: (1) regulatory advantages, (2) demand advantages and (3) technological advantages.

(1) Regulatory advantage: Shanghai's lead market potential for waste management technologies is strongly constituted by a regulatory advantage due to the waste classification law. Shanghai was the first major city-region in China to introduce a sophisticated waste sorting system in 2019, classifying household waste into dry, wet, recyclable and hazardous. Residents and companies face fines if they violate the waste sorting regulations, which ensures an effective adherence to the sorting system (M.-H. Zhou, Shen, Xu, & Zhou, 2019). The implementation of this waste sorting system is an illustrative example of what Rennings (2000) discusses as regulatory push for environmental innovation. The regulation increases efficiency of waste incinerators,

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[16] See Yunnan Province Domestic Waste Incineration Power Generation Medium and Long-term Special Plan (2019-2030) and Henan Province Domestic Waste Incineration Power Generation Medium and Long-term Special Plan (2018-2030), both in Chinese. There are similar plans for at least 13 more provinces and cities.

supporting diffusion of such plants. In addition, Zhou et al. (2019) argue that the new regulatory and legal system for waste classification in Shanghai will be an exemplary model and will serve as a benchmark for implementing similar regulations in other Chinese regions. If similar regulations are also introduced in other countries, Shanghai's lead market potential will be further strengthened. Usually, infrastructure-related innovations are subject to a triple regulatory challenge due to monopolistic bottlenecks and static grid systems (Walz, 2007). The waste management system, however, is not entirely based on existing infrastructure, which counteracts the triple regulatory challenge. Furthermore, the waste incineration industry only faces a natural monopoly on the regional level with one or few actors per region, allowing for competition between those actors for entering new regional markets. As the industry is in a developmental stage and a transition from landfills to waste incinerators is sought in China and many other countries, the competition for entering new markets is further strengthened (Yun Li et al., 2015).

(2) Demand advantage: Demand advantages in Shanghai primarily take effect due to the city’s population size. This is, of course, reflected in Shanghai’s energy demand. Due to still increasing levels of urbanization and energy consumption per capita, it is assumed that demand for energy will continue to grow (C. Zhang & Lin, 2012). At the same time, emissions ought to be reduced. This triggers the need for more environmentally friendly modes of energy production such as waste incineration. Moreover, Shanghai ranks second in the amount of municipal waste produced among Chinese cities, with only Beijing having produced slightly more. However, given the higher population density of Shanghai, appropriate waste management is more difficult. The demand for waste management innovations in Shanghai is also considerably higher than for other megacities such as Chongqing, Chengdu or Tianjin, which despite their size produce less municipal waste (Ministry of Ecology and Environment (MEE), 2018b). Shanghai’s prominence among Chinese cities regarding waste production is not only based on quantities, however. Due to the fact that Shanghai’s population is arguably among China’s most metropolitan in terms of lifestyles as well as patterns of working, housing, and consumption, this city exemplifies today what many other cities will experience in the near future (S. Chen & Lamberti, 2015). In general terms, Shanghai’s waste production and energy consumption is indicative of trends that are likely to develop in other Chinese regions as well.

Figure 4: Waste-related patents in China, patent families from 1970 to 2010, prefecture level
(data: GreenTechDB; Perruchas et al., 2020)

(3) Technological advantage: We have argued, however, that supply-side mechanisms (technological advantages) are also crucial for regional lead markets to develop, as this is closely linked to the other regional-level lead market factors: regulation and demand (see Figure 3). In order to reveal the regional concentration of innovation activities, which indicate the technological advantage of regional lead markets, we make use of novel patent data from GreenTechDB (Perruchas et al., 2020). Analyzing patent data is the standard approach for uncovering the technological advantage of lead markets (Horbach et al., 2014; Köhler et al., 2014; Walz & Köhler, 2014). Using information on inventor locations, we mapped the total patent counts of waste-related technologies according to ENV-TECH: 1_3 waste management (1699 patents), 8_2 solid waste management (6194 patents) and 4_2 energy generation from fuels of non-fossil origin including incineration technologies (4566). Figure 4 shows the spatial variation of these technologies on the prefecture level, pointing to clear technological advantages

of Shanghai, Shenzhen and Beijing in waste-related technologies (see Figure A.2 for a standardized version). Shanghai’s technological advantage in waste-related technologies is further supported by RPA[17] figures based on patent applicant addresses. We find that Shanghai has an RPA of 34.6 in waste-related technologies, indicating a strong technological specialization. However, it is not only the overall regional technological capabilities in Shanghai but also the financial and technological strength of the municipally-owned company that accounts for the technological advantage. This company is assumed to be capable of taking a leading position in the industry, entering new regional markets (Li et al., 2015, p. 236). Shanghai thus not only provides strong capabilities in waste-related technologies, but also features capable actors. This is also evident from the network of companies involved in the construction of the plant. Companies involved in planning, design, engineering and construction were mostly from the Shanghai region, while some additional technological components came from Japan and Germany. Scaling and combining different technologies to meet the plant’s size demonstrates the technological capabilities for waste management in Shanghai.

In conclusion, it is the combination and interplay of all three RLM factors that constitute the lead market potential in Shanghai, outperforming Shenzhen and Beijing as potential lead markets for waste-related technologies. A simple geography of innovation perspective on technological capabilities would not allow the determination of the regional lead market potential: ‘*the large market as well as the legal conditions in Shanghai made it possible to develop and operate the world's largest waste incineration plant*’ (authors’ translation from interview I.SIP.1). This also highlights the interplay of different regional lead market factors, as demand and regulation seem to further strengthen the technological advantage in Shanghai. On the other hand, the technological advantage (i.e. operating the incineration plant) strengthens the effectiveness of the waste sorting regulation and demonstrates its flagship role, while also creating demand for separating and incinerating waste vis-à-vis landfilling. However, it is too early to predict whether Shanghai can exploit its lead market potential in the near future and whether sophisticated waste incinerators, following the Shanghai model, will diffuse nationally and globally. Yet, strategic plans for China’s provinces (see 5.3) as well as global demand for environmentally friendly waste management solutions (Kaza et al., 2018) allow a forecast and support this assumption.

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[17] Further information on the RPA is provided in Appendix A.

Altogether, the case of waste management in Shanghai demonstrates the applicability of the regional lead market concept. We find illustrative evidence on early innovation diffusion processes that can be explained using three RLM factors. That is to say, government authorities from various Chinese regions are interested in copying the Shanghai model of waste management and frequently visit the plant and engage in negotiations.

2.6 Discussion and conclusion

Regional lead markets (RLM) for environmental innovation are sub-national regions with large markets that adopt a later successful innovation at an early stage and gain competitive advantage in the respective industry. RLMs can drive national and international diffusion processes and global standardization. RLMs might emerge in specific empirical contexts where the national lead market framework is less applicable, as lead market factors are constituted on the regional level. We have provided illustrative evidence on the lead market potential of Shanghai for waste management innovations and have demonstrated the framework's applicability.

The results of this article are important for both academia and practical application. Firstly, we contribute to filling research gaps in the geography of sustainability transitions literature, as we provide building blocks for a hitherto lacking regionalized framework that aims to explain the diffusion of environmental innovations. The RLM framework complements the existing body of heuristics and concepts, and provides an approach towards understanding and examining processes at the sub-national scale. In addition to this theoretical input, our paper contributes to the empirical analysis of lead markets. That is, a regional lead market is constituted by three major factors (regulation, demand, and technology) which can be easily operationalized and measured on the regional level, paving the way for quantitative studies. Future country-level lead market studies should thus pay attention to the regional dimensions of lead market factors, in particular in the case of large countries with distinct regional profiles. Secondly, we call on policymakers, firm executives and further stakeholders to acknowledge the regional constitution of transitions and innovation diffusion processes. Therefore, a reassessment of regional policy making and interaction is crucial to design conditions for lead market factors to arise, or rather to strengthen existing advantages. Given the importance of the lead market concept in national and international policy making (Quitzow et al., 2014), it might also prove useful for regional innovation policies.

The RLM concept as well as the illustrative evidence provided for the case of Shanghai are constrained by some limitations that deserve a brief discussion here. Our framework takes a rather holistic approach and needs to be adjusted to the empirical context. As Walz and Köhler (2014) point out, a distinction between infrastructure-related innovations (water, transport, energy supply) and eco-efficiency innovations (energy use, material use) is crucial, as the respective regimes differ in adaptability and in relation to their corresponding niches. Future research needs to add this differentiation to the framework. Moreover, it is not yet clear how the spatial diffusion of environmental innovation actually transpires. Following the recent arguments of technology transfer within countries, the concept of anchor regions might provide starting points to resolve this void (Seo & Sonn, 2019b). Most importantly, we developed the RLM framework with a focus on China, as the Chinese case offered useful properties for illustration such as the country's market size, regional differences in factor endowments or the regulatory power of regional governments. This context, of course, is not given in all countries. However, we argue that the framework can be applied to study regional lead markets in, for example, India, Germany, the United States or other countries with large markets. In fact, the spatiality as well as the importance of lead market factors varies according to the empirical case. For a regional lead market in a country other than China, a strong technological or demand advantage might thus compensate for a weaker regional regulatory advantage. Moreover, the RLM framework serves as a general heuristic for studying lead markets with an emphasis on geographical sensitivity. It thus also allows deeper insights into the lead market factors of country-level studies.

Further research is needed in several areas. Firstly, empirical research is important to both test and advance the concept of regional lead markets. That is to say, current research is mostly conducted in a case-study design (e.g. Horbach, Chen, and Vögele 2014; Lacerda et al. 2014; Rennings and Smidt 2010). This might be reasonable with the a priori assumption of lead markets being countries, limiting data to a small number of observations. Following our call for a regional perspective on lead markets, however, large-scale quantitative data analysis is needed to complement case-study findings, including the empirical part of this paper. This corresponds to the argument put forward by Köhler et al. (2019: 18) '*the increasing wealth of case materials creates demands and opportunities for methodological approaches that reach for generic* *insights across cases'*. Hence, appropriate indicators for RLM factors need to be tested and innovative data sources for analyzing early market formation and innovation adoption need to be explored. Following our reasoning that regulation, demand and technological capabilities mainly constitute lead markets on a regional level, assessing indicators for these three factors should be sufficient to analyze regional lead market potentials. This further facilitates empirical analyses. Secondly, further research on how the different lead market factors are in fact regionally or nationally constituted is needed, leaving room for future multi-scalar perspectives. This, of course, also depends on the empirical case and the innovation under study. Thirdly, as we only provide illustrative evidence on the case of waste management in Shanghai, there is high demand for in-depth studies on this particularly interesting case (e.g. Zhou et al., 2019). Lastly, we call for further theorizing efforts in the geography of sustainability transitions community (see also Binz et al., 2020), as the concept of regional lead markets is only applicable to analyze innovation diffusion. However, due to the complex nature of transitions, aspects such as social dimensions of transition processes also demand comprehensive regionalized frameworks, building foundations for future empirical work (e.g. Chlebna & Mattes, 2020).

CHAPTER THREE

The Geography of Green Technology Licensing in China

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Abstract

Heatmap techniques are used to visualize the geography of green technology license agreements in China. The map is based on unique patent and licensing data, linking regional technology development (licensors) to regional technology adoption (licensees), thus allowing the study of diffusion patterns of green technologies. It highlights the fact that most green technology license agreements are concluded within the same region, which is often neglected when studying diffusion processes from a network perspective. Heatmaps allow a better interpretation of network data, in particular for networks with many loops when compared to classical network visualizations.

The adoption of green technologies is crucial for tackling climate change and for offering solutions to resource depletion and further environmental challenges. While there is a growing body of literature on the geography of green technology development (Barbieri, Perruchas, et al., 2020), research on adoption and diffusion is scarce. This graphic provides information on the geography of license agreements for green technology patents in China, highlighting the importance of intra-regional diffusion processes.

A license agreement is a contract between a licensor (patent owner) and a licensee who is authorized to make use of the technology. Licenses thus allow the measurement of both innovation development and innovation adoption. The data underlying this graphic was retrieved from IncoPat, a Chinese patent database listing license agreements. Green technology patents were identified using the ENV-TECH classification (Haščič & Migotto, 2015). Then, a geocoding process was employed to regionalize the licensor and licensee addresses to the prefectural level, resulting in a data set of 9396 license agreements for 8565 patents. To be specific, licensor addresses from the patent documents were geocoded using the open source GeoNames database, while licensee names (e.g. firms, universities) were used to obtain locations via Google Maps and Baidu Maps API queries. In a final step, licensors and licensees were aggregated to 294 prefecture-level regions. Based on the regional information for licensor-licensee linkages, a directed asymmetric adjacency matrix A with the dimensions 294 × 294 was constructed, with cells a_{ij} indicating the number of licensed patents from source region (licensors) i to target region j (licensees). This data representation allows a study of the diffusion of technologies in detail, which is usually done in network visualizations (Gui, Du, & Liu, 2019). However, this often leads to neglecting the importance of intra-regional licensing. In fact, I find that about 57 percent of all license agreements for green technologies are concluded intra-regionally, leading to a relatively sparse network of diffusion. The share of intra-regional licensing, however, differs between regions (e.g. Guangzhou 43 percent, Shanghai 49 percent, Nanjing 54 percent, Beijing 51 percent, Shenzhen 70 percent, and Chongqing 82 percent).

Heatmap visualization techniques help to analyze network loops in that respect, while (spatial) network visualizations often lead to an overestimation of the value of inter-regional linkages (e.g. Gui, Du and Liu, 2019). This graphic adds to the literature arguing that knowledge diffusion via license agreements relies on geographic proximity and established local collaborations (Bidault & Fischer, 1994; Seo & Sonn, 2019a). Moreover, the findings support arguments for regional specificities of sustainability transitions, as the development and adoption of green technologies often seems to occur within close geographic boundaries (T. Hansen & Coenen, 2015).

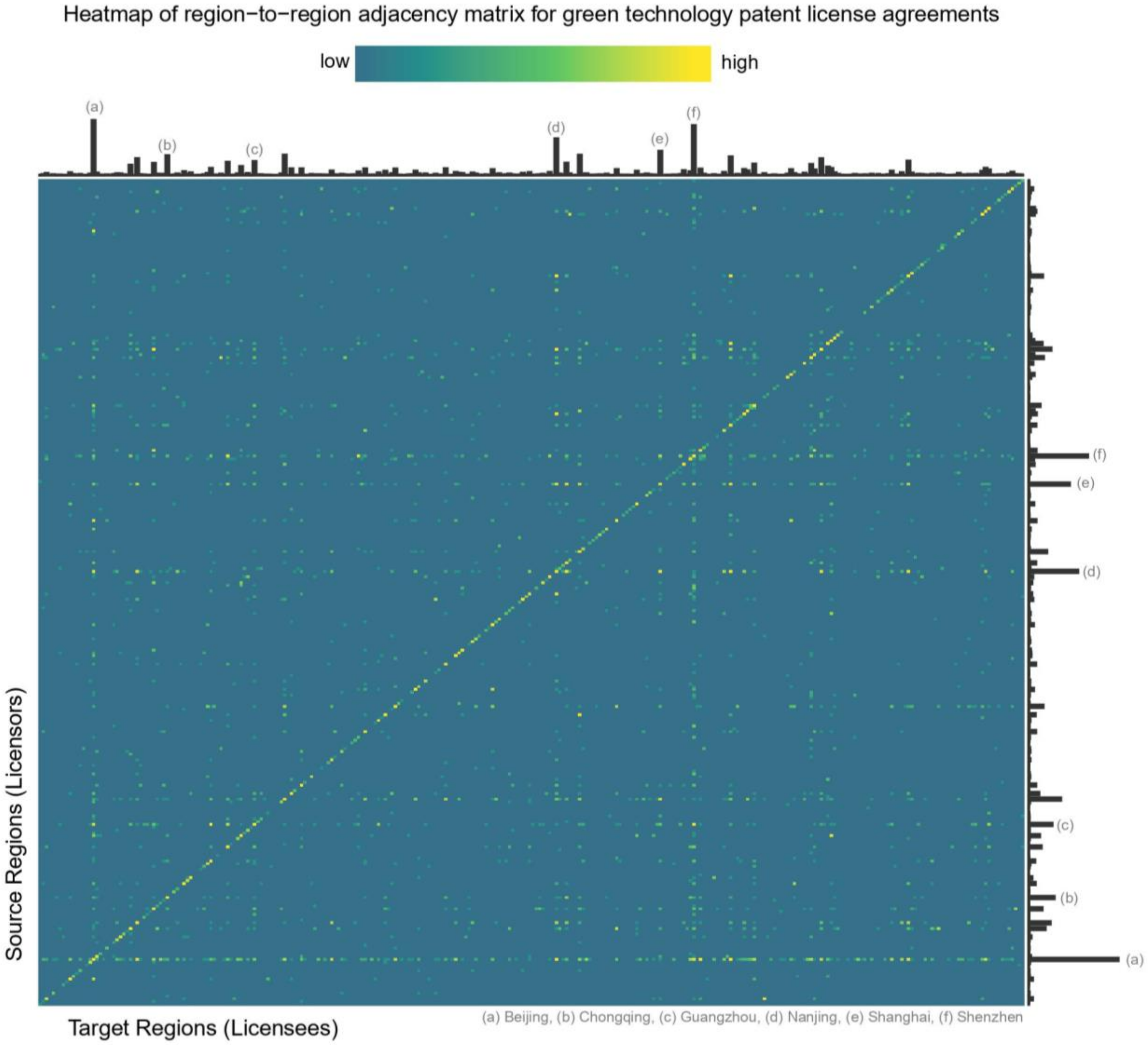

Figure caption: Heatmap of region-to-region adjacency matrix for green technology patent license agreements. High number of license agreements indicated by light color (log scale). Bars indicate number of licensors (right) and licensees (top) per region. Licensing data retrieved from IncoPat (www.incopat.com), graphic created in R using the superheat package (Barter & Yu, 2018). Licenses with commencement dates ranging from 2008-2019, design patents are excluded.

Figure 5: Heatmap of region-to-region adjacency matrix for green technology patent license agreements

CHAPTER FOUR

License to Green: Regional Patent Licensing Networks and Green Technology Diffusion in China

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Abstract

Based on the concept of regional lead markets for environmental innovation, this paper fits exponential random graph models on a regionalized patent licensing network to explore how green technologies diffuse in space. The empirical analysis relies on a novel database of license agreements for Chinese patents, which are used to measure spatial innovation diffusion, as they indicate locations for both innovation development and adoption. Findings suggest, among other factors, that geographic proximity matters, that regions exhibit both network activity and popularity effects particularly in highly populated regions, that network effects such as mutual linking and triadic closure help to explain diffusion processes, and that local technology supply and demand are closely interconnected. In that regard, the role of environmental regulations is identified as being complex. The findings help to understand the formation of regional lead markets for environmental innovation, opening opportunities to accelerate innovation diffusion and a transition towards sustainability.

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4.1 Introduction

Adopting green technologies is an important ingredient for a societal transition towards cleaner and more sustainable modes of production and consumption. Green technologies help to reduce environmental harm, to mitigate climate change and to prevent resource depletion. Accordingly, there has been much research on factors affecting the development of green technologies and environmental innovations (Hojnik & Ruzzier, 2016; Horbach, 2016). Given that most green technologies are currently escaping their technological niches, the transition towards sustainability is leaving a phase of emergence and entering a new phase of acceleration (Markard, Geels, & Raven, 2020). For this new phase, it is crucial to understand innovation diffusion processes in order to design appropriate policy tools which can help to accelerate green technology adoption. In that respect, innovation diffusion means that an innovation is adopted by an actor other than the innovator. From a spatial perspective, diffusion can occur within a region (intra-regional diffusion) or between different regions (inter-regional diffusion).

Against this background, the concept of regional lead markets suggests that the inter-regional diffusion of innovations depends on leading regions that demonstrate an innovation's benefits and act as lighthouses, with other regions following their example (Beise, 2004; Beise & Rennings, 2005b; Losacker & Liefner, 2020b). A lead market can thus drive spatial innovation diffusion and set technological standards while increasing regional competitive advantages, making the concept highly interesting for policymakers (e.g. Edler et al., 2009). Several factors have been identified in the literature that contribute to the emergence and formation of a lead market, i.e. regional technological advantages, regulations and demand (Losacker & Liefner, 2020b; Quitzow et al., 2014). This perspective on regional advantages postulates that innovations will diffuse from the regional lead markets to other regions. However, it has not yet been comprehensively established, neither conceptually nor empirically, how the spatial diffusion of environmental innovations - from a lead market region to other regions - actually occurs once a lead market has emerged. In light of this, this paper aims to contribute to recent theoretical advancements of the lead market concept by providing empirical insights on the spatial diffusion of green technologies. That is to say, previous advancements have focused on conceptualizing lead market factors, while less scholarly work has been dedicated to exploring the phase of innovation diffusion within the lead market concept (Losacker & Liefner, 2020b; Walz & Köhler, 2014).

In this paper, a unique data set on license agreements for green technology patents is used to unveil the regional patterns of innovation diffusion in China, with China having the largest market for green technologies (see GreenTechDB by Perruchas et al., 2020). License agreements indicate the commercial application and market entry of an innovation and allow the localization of both innovation development and innovation adoption. Building on that, a regional patent licensing network is used to analyze the diffusion of green technologies on the prefectural level. The results help to shed light on the following research questions within the lead market literature:

Which regional and network-specific characteristics affect the inter-regional diffusion of green technologies in the context of regional lead markets? In which spatial patterns are these diffusion processes organized?

The remainder of this paper is structured as follows. Section 4.2 discusses the foundations as well as the current state of research on environmental innovation and green technologies in the Chinese context. In addition, spatial innovation diffusion is addressed and the concept of lead markets is briefly reviewed. In section 4.3, the data set is presented and the methods for network analysis are introduced. Section 4.4 contains a description and discussion of the results and points out some limitations. Section 4.5 presents the conclusion.

4.2 Theoretical background

4.2.1 Environmental innovation and green technologies in China

Environmental innovations are new or improved products or processes which reduce environmental risk, pollution, and other negative impacts of resource and energy use compared to alternatives (Arundel & Kemp, 2009; Kemp et al., 2019). Despite many further interpretations such as organizational or business model types of environmental innovation, the notion of environmental innovations is narrowed for the sake of this paper to practical applications of green technologies. These green technologies, however, feature some peculiarities compared to regular (technological) innovations.

That is to say, they might lead to win-win situations: reducing environmental harm on the one hand and increasing profits on the other. However, firms often do not recognize this opportunity due to inherent uncertainties in R&D processes and incomplete information (Barbieri, Ghisetti, Gilli, Marin, & Nicolli, 2016; Horbach, 2008; Porter & van der Linde, 1995). Moreover, firms tend to underinvest in environmental innovations due to a double-externality problem. Environmental innovations entail positive spillovers both in the innovation and the diffusion phase. The former encompasses knowledge spillovers resulting from R&D activities akin to regular innovations, while the latter involves reducing external costs in the form of environmental burden. This situation leads to market failures, requiring policy action and regulatory pressure (Faber & Frenken, 2009; Rennings, 2000). Therefore, regulatory measures are needed, forcing firms to adapt to environmental friendly modes of production, and to eventually develop or adopt environmental innovations.

In addition to the societal and environmental benefits, the green growth narrative suggests that green technologies offer promising means for regional economic development (Capasso et al., 2019; Gibbs & O'Neill, 2017; Jänicke, 2012), as green technologies differ from non-green technologies in terms of complexity and impact. On the one hand, green technologies rely on more diverse knowledge and combine more technological components, while on the other hand, they appear to have a higher impact on future inventions, enabling opportunities in a wide range of economic sectors (Barbieri, Marzucchi, et al., 2020). As knowledge involved in complex technologies is highly sticky (Balland & Rigby, 2017), green technologies are more likely to be place-bound, highlighting the role of geography for the analysis of environmental innovations. Furthermore, green technologies rely on higher degrees of R&D cooperation and external knowledge sources when compared to non-green technologies (De Marchi, 2012; Ghisetti et al., 2015; Horbach, Oltra, & Belin, 2013), which is also reflected in the importance of regional collaborations and proximity to universities (Horbach, 2014; Quatraro & Scandura, 2019). The role of geography for environmental innovations is further strengthened by regulations and policies on the regional level (Losacker & Liefner, 2020b).

Moreover, many green technologies are in an emerging stage of the technology life cycle, which might allow regions to create new developmental paths or to diversify into green industries (Barbieri, Perruchas, et al., 2020; Grillitsch & Hansen, 2019; van den Berge et al., 2020). This is crucial for catch-up processes in emerging economies (Lema & Lema, 2012; Quitzow et al., 2017), but also facilitates leapfrogging and the formation of lead markets (Binz et al., 2012; Horbach et al., 2014).

In this regard, emerging economies, China in particular, might take over international leadership based on ‘green windows of opportunity’ (Lema et al., 2021). In fact, China has been able to catch up rapidly over the past two decades and is currently market leader in many green technologies such as solar PV (Ely et al., 2019; Huang & Lema, 2021). However, China's role in global innovation systems is not limited to manufacturing and green technology development. Rather, China is increasingly in a position to shape global socio-technical regimes (Gosens et al., 2020). China has been able to achieve this position in particular through a shift to an innovation-based economy, which is reflected in the focus on green technologies and sustainable development in China's 5-year plans (e.g. 12th, 13th and 14th plan). At the same time, the Chinese central and local governments have responded strongly to environmental concerns and strengthened environmental policies, as evidenced by China's ambitious plans to become climate neutral by 2060. Despite these general trends, China's positive development is mainly driven by a few regions of the country, as significant regional disparities prevail in terms of economic strength and innovativeness (Kroll & Neuhäusler, 2020). Due to the economic conditions and lacking innovation capabilities in some less developed Chinese regions, environmental protection targets may not be met. In fact, it has often proved impossible to achieve the ambitious goals set by the central government at the local level, pointing towards an implementation gap (Brehm & Svensson, 2020; Kostka & Mol, 2013). The interplay between regional environmental regulations and regional innovation capacity is therefore more prominent in China than in other nations. This is also due to the fact that regions in China are often used as pilot areas for testing emerging technologies and policy measures (Heilmann et al., 2013), making China an interesting case to study the spatial diffusion of environmentally benign technologies.

4.2.2 The spatial diffusion of environmental innovation and the lead market concept

Understanding innovation diffusion processes is particularly important for the case of green technologies, as a transition towards more sustainable modes of production and consumption requires not only the development of these technologies, but actual innovation adoption (Du, Li, & Yan, 2019; Ghisetti, 2017; Hojnik & Ruzzier, 2016). In light of this, there is a growing body of literature on the geography of sustainability transitions arguing that the regional dimension is key to understanding innovation adoption dynamics and patterns (Truffer, Murphy, & Raven, 2015). Among other factors, it is regional visions, institutions as well as the technological and industrial specialization of regions which can promote a transition towards sustainability based on green technologies (T. Hansen & Coenen, 2015). Successful regions can take a pioneering role and act as lighthouses, triggering other regions to follow their sustainable path (Cooke, 2011). Building on that, regions can become lead markets for environmental innovations. Lead market regions are first to adopt a subsequently successful innovation, driving global innovation diffusion, strengthening dominant designs, setting technological standards and increasing the regional competitive advantage (Beise & Rennings, 2005b; Huber, 2008; Losacker & Liefner, 2020b). The formation of regional lead markets for environmental innovation requires the support of three major factors:

(1) *Regulatory advantages*: effective regulatory measures in the lead market might also be implemented in other administrative regions or countries. In more detail, the lead market potential for a specific environmental innovation increases when successful regulations in the lead market also prove useful for other regions.

(2) *Demand advantages*: regional conditions can increase the demand for a specific environmental innovation. Over time, other regions might anticipate the benefits of this innovation, triggering innovation diffusion.

(3) *Technological advantages:* the lead market potential for a specific innovation also depends on the region's existing technological capabilities, as these regional capabilities lead to intra-regional diffusion and early market formation processes in the region through, for instance, user-producer interactions (Dewald & Truffer, 2012).

While knowledge on traditional lead market factors for environmental innovation is extensive and well-researched (Beise, 2004; Beise & Rennings, 2005b; Köhler et al., 2014; Rennings & Smidt, 2010), the importance of technological advantages has only recently attracted attention in the lead market literature (Horbach et al., 2014; Quitzow et al., 2014). However, the three factors are strongly interdependent and might reinforce each other, eventually leading to the formation of a regional lead market (Losacker & Liefner, 2020b). That is to say, regional environmental regulations and policies have a major impact on regional technological capabilities and on the diffusion of environmental innovations within the region (Horbach, 2016). At the same time, regional supply and regional demand of environmental innovations co-evolve in market formation processes (Dewald & Truffer, 2012). In China's place-based policy approach, regional regulations and policies often depend on the local context such as technological specialization or demand conditions (Heilmann et al., 2013; Lauer & Liefner, 2019). Regional lead markets thus arise from the interplay of regional regulatory advantages, regional demand advantages and regional technological advantages. Analyzing these factors allows the identification of potential lead markets and helps to understand the development of lead markets ex-post. Also, the recent reconceptualization by Losacker and Liefner (2020) helps to uncover the spatiality of lead market factors as well as the geography of lead market formation in more detail. Within the lead market literature, however, it still remains unclear how the spatial diffusion of environmental innovations from the lead market region to other regions actually occurs. More accurately, the scholarly work on lead markets is mainly concerned with explaining the lead market phenomenon for a specific technology based on the different lead market factors, while less effort has been spent to study the actual innovation diffusion phase and its mechanisms.

Traditionally, it has been argued that the diffusion of innovations follows a specific spatial logic, with geographic proximity increasing the likelihood of adoption (Hägerstrand, 1967). For instance, previous research has established that externalities, which trigger the adoption of new technologies, are stronger in a regional cluster with short distances between innovators and early adopters (Antonioli et al., 2016; Baptista, 2000; von Graevenitz, Graham, & Myers, 2021). Moreover, it is assumed that inter-regional diffusion will reach regions with high population and demand in an early phase, and then smaller regions in close geographic proximity to those early adopters later on, highlighting the importance of network mechanisms and regional hierarchies (Lengyel et al., 2020). Lengyel et al. (2020) also suggest that spatial proximity plays a more important role for complex technologies such as green technologies, which is in line with the reasoning in section 4.2.1. In contrast, Ocampo-Corrales et al. (2021) show that knowledge flows for green technologies (i.e. renewable energy technologies), indicated by patent citations, are not localized but rather span large distances. However, patent citations are a weak proxy when it comes to analyzing innovation diffusion. The following section suggests using patent license agreements as an indicator for innovation diffusion instead, which will be helpful to answer the paper's research questions.

4.2.3 Measuring innovation diffusion: the merits of patent license agreement data

Research on technological innovation strongly relies on the availability of appropriate indicators. Usually, patent-based measurements such as inventor locations are employed to study where innovative activity takes place. In order to map knowledge flows and innovation diffusion, scholars frequently track patent citations or co-inventions. Despite the many advantages of conventional patent data, a major problem remains: most patents only represent inventions and not innovations that are introduced to the market and find commercial application (Archibugi, 1992). To overcome this problem and to measure innovation in a more market-oriented way, this paper relies on geocoded patent licensing data. Patent licenses are contracts where one party, the licensor, authorizes another party, the licensee, to use his/her patented invention for commercial purposes. Both parties hence consciously agree on an economic value of the patent. Patent licenses thus indicate the commercial application of an invention, allowing for the use as a proxy for innovation adoption and diffusion (Nelson, 2009). In addition, patent licenses enable the analysis of the direction and spatial scope of innovation diffusion from licensors to licensees. License agreements can thus be considered as a rich indicator for the analysis of innovation diffusion, as they track the diffusion process from the technology source to its market utilization. However, licensing information is difficult to obtain or is unavailable in most cases, and is hence seldom used in empirical research (e.g. Caviggioli et al. 2020; Seo and Sonn 2019a).

Figure 6 demonstrates how license agreements can be used to study the spatial diffusion of innovations. License agreements between different actors (firms, universities, research institutes, etc.) simultaneously represent the application of an invention and the diffusion of this innovation in space. For instance, inter-regional innovation diffusion from region *A* to region *B* can be assumed, as license agreements are concluded between licensors in region *A* and licensees in region *B*. This diffusion pattern, of course, is not always unidirectional and can be reciprocated as visualized by the mutual link between region *A* and region *C*. License agreements concluded between two actors in the same region represent intra-regional innovation diffusion.

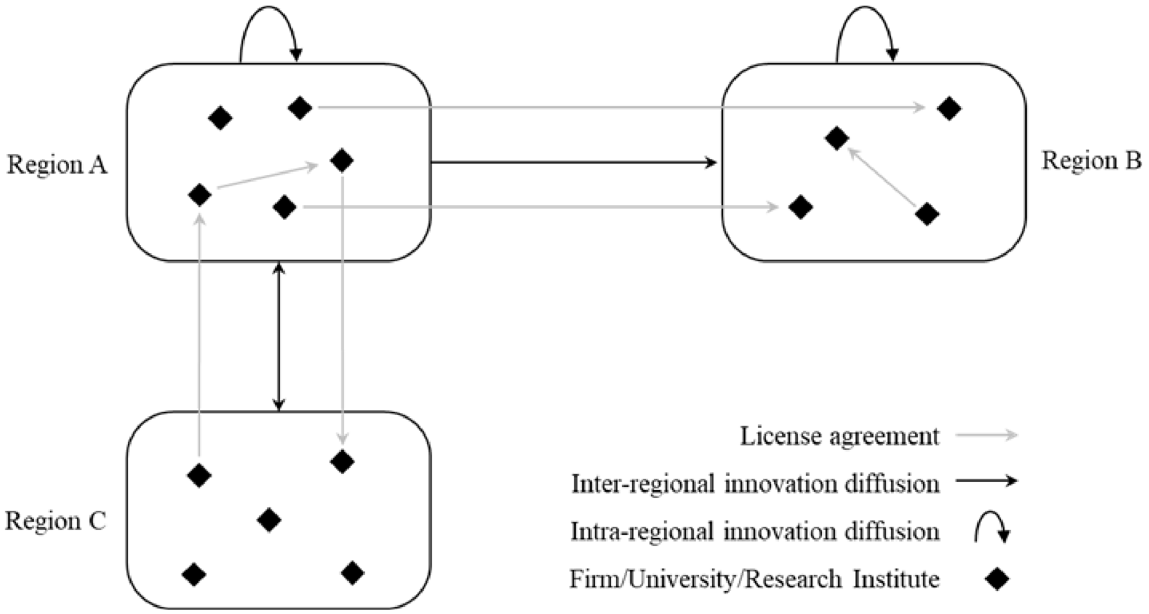

Figure 6: Conceptual framework: spatial diffusion of innovations

With respect to the regional lead market framework, license agreements inherently measure regional demand and regional technological advantages. That is to say, out-licensing figures of a region display its demand advantage, as technologies developed in this region are economically utilizable in other regional markets. On the other hand, regional in-licensing figures allude to market formation processes, with intra-regional licensing representing the interconnectedness of local technology supply and demand. The empirical part of this paper will help to shed light on the spatial organization of this regional licensing network and its implicit innovation diffusion processes, advancing the knowledge on regional lead markets. In particular, the analysis will look into the characteristics affecting inter-regional diffusion on three levels: characteristics of the region (network node), characteristics of the relationship between two regions (network tie), and characteristics of the underlying patterns (network structure).

4.3 Data and methods

4.3.1 Data source

For this study, the IncoPat Global Patent Database (www.incopat.com) is used to retrieve patent and licensing information. IncoPat is a Chinese database which sources patent data directly from the Chinese Patent Office (CNIPA) and matches legal data such as license agreements from further CNIPA documents that cannot be collected via

CNIPA's own database or other renowned databases such as Patstat.[18] IncoPat thus adds great value to regular patent data and is increasingly used in empirical research (e.g. He et al., 2019; Losacker, 2020; Yang et al., 2019; Yu, 2017). All licensed Chinese patents (granted inventions and utility models, not design patents) with license commencement dates between 2008 and 2019 were collected from IncoPat.[19] In order to filter green technologies, the OECD ENV-TECH classification by Haščič and Migotto (2015) was used, which is standard in research on green technologies (e.g. Barbieri et al., 2020; Kemp et al., 2019; Perruchas et al., 2020). ENV-TECH links IPC and CPC classes to a total of eight environment-related domains, 36 subgroups and 95 technologies (domains and subgroups are listed in Table A.2 in Appendix A). This led to a set of 10,983 green technology patents with license agreements in China. A flowchart visualizing the data processing is provided in Appendix B in Figure A.4.

4.3.2 Regional patent licensing network

In order to build a regionalized data set, both licensor and licensee addresses were geocoded to the prefecture level. However, different geocoding strategies for licensors and licensees were used owing to differing data availability.

(1) *Licensors*: In principle in a license agreement, the licensor is the patentee. The patentee, in turn, is also most often the patent applicant whose address information (i.e. city) is available in IncoPat for every patent document. Hence, patents in which the applicant is also the patentee and thus the licensor were filtered. This held true for about 85 percent of all patents in the data set (9,320 of 10,983). Next, the addresses were passed through GeoNames to retrieve coordinates for each prefecture or city.[20] The remaining 9,320 patents equal a total of 10,707 license agreements, with some patents being licensed multiple times.

(2): *Licensees*: The license agreement data in IncoPat only allows the retrieval of licensee names and does not provide address information. However, licensees are usually firms, universities or research institutes, which enables the identification of

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[18] The author conducted several checks to test the quality and coverage of IncoPat by comparing it with CNIPA data. IncoPat covers about 99.8 to 100 percent of all patents registered at CNIPA, which is robust for various periods as well as various technology classes.

[19] The recording of license agreements started in 2008. Note that the license commencement date is on average 1065 days after the patent application date and 534 days after the publication date.

[20] GeoNames is a free geographical database under a creative commons attribution license 4.0 and can be reached via www.geonames.org using API web services, but it also provides download options. The database contains more than 25 million geographical names such as cities, provinces, lakes and the like. It also lists alternate names and languages which ensures high quality geocoding.

addresses via web search. Accordingly, two web search engines were used to geocode licensee addresses: Google Maps and the Chinese Baidu Maps. In order to retrieve the addresses, automated queries for all licensee names were initiated in both search engines, using their programming interfaces (API).[21] The final licensee addresses were identified following a three-step validation and quality check process. Firstly, results of Baidu Maps and Google Maps were compared: if Google and Baidu found the same address, it was assumed to be valid (6,919 cases). Secondly, for Baidu, the API query returns parameters indicating the analytical quality. Those addresses for which Baidu's comprehension of the queried address string was high and the analytical error was less than 5km were kept (878 cases). Thirdly, for Google, the API query returns parameters on the search quality in a similar manner. Those additional addresses from Google for which the search yielded results with high accuracy were also kept (1,915 cases). Altogether, valid addresses for 9,712 licensees (of 10,707) were found, which is about 91 percent of all licensees. The remaining licensees could not be geocoded due to employing rather strict filters to minimize the number of false addresses (see above), some licensees (i.e. firms) might not exist anymore or may have changed their legal name, and some licensees are individuals. In a final step for regionalization, GADM data was used to aggregate licensor and licensee coordinates to the prefecture level.[22] Finally, the results were intensively checked and cleaned manually (e.g. revising homonymous prefectures) and foreign addresses were removed. The final data set contains geographic information for 9,396 green technology license agreements in China (8,565 patents) regarding where the technology originates from (licensor region; source region) and where it finds commercial application (licensee region; target region). This information was used to build a regionalized patent licensing network with 344 prefecture-regions as nodes, while the license agreements result in 1,685 valued and directed links (without loops). This corresponds to a network density of 1.43 percent. The network with prefecture centroids as nodes is visualized on a map in Figure 7.[23]

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[21] APIs are programming interfaces which allow large-scale queries for the respective engines (Google and Baidu). To make use of that, one needs to register an API key for both platforms. Information for Google Maps API can be found here (cloud.google.com/maps-platform). Information for Baidu Maps API (in Chinese) can be found here (lbs.baidu.com/index.php?title=webapi).

[22] I used GADM version 3.6 (www.gadm.org). GADM provides spatial data such as shapefiles free of charge for academic use.

[23] Figure 7 does not visualize loops and isolates. The node size denotes degree centrality.

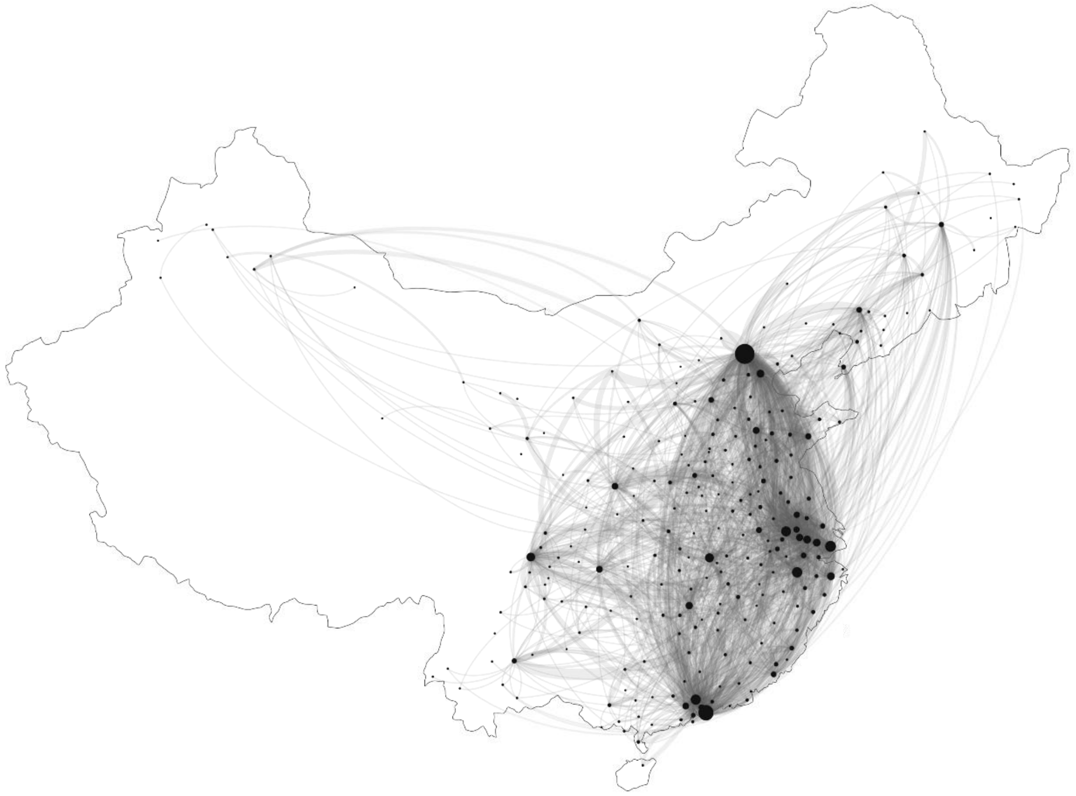


Figure 7: Regional green technology patent licensing network

In fact, most licensees (about 57 percent) are located in the same prefecture-level region as the respective licensor, which has been discussed in another article (see Losacker 2020). The high level of intra-regional licensing is in line with previous research on the geography of licensing activities (Mowery & Ziedonis, 2015). The main reasons for intra-regional licensing from the licensee perspective are that finding an appropriate technology involves high transaction costs, such as identifying the potential partner, negotiating prices, transferring knowledge etc., which is easier if licensor and licensee already know each other or are located in the same region (Bidault & Fischer, 1994; Seo & Sonn, 2019a). To some extent, this sheds light on the paper's research questions, suggesting that regional technological advantages are of great importance for analyzing the lead market potential of regions. Given that most patents are licensed within a region, regional technological advantages and the emergence of a lead market (i.e. diffusion) demonstrate feedback effects, with intra-regional diffusion reinforcing the regional technological capabilities, for example through learning from early adopters (Olson, 2018). What still remains unclear, however, is how inter-regional diffusion is organized.

4.3.3 Exponential Random Graph Model

In recent years, ERGMs have proven to be a valuable methodological approach to study (regional) knowledge and innovation networks (Broekel et al., 2014; Broekel & Bednarz, 2018; Broekel & Hartog, 2013; Juhász, 2021; D. Ma, Yu, Li, & Ge, 2021). ERGMs are a class of statistical models used to study networks and can account for dependencies in network structures. More specifically, ERGMs can predict the presence of a tie between two nodes in a network from given network configurations. These configurations can be covariates at the node and tie level, but also structural network variables. In this context, ERGMs are often compared to logistic regressions, as both models predict a binary variable (i.e. presence of a tie). In the literature on network models, scholars distinguish between dyad-independent (e.g. node attributes) and dyad-dependent (e.g. degree distributions) terms. While the former can be employed in basic regression models, the latter causes complex cascade effects, which requires more sophisticated modeling techniques such as ERGMs, as the assumption of statistical independence of observations is violated. Lusher et al. (2013) denote a general form of an exponential random graph model as:

$$P_\theta(x) = \frac{1}{k(\theta)} \exp(\theta_1 z_1(x) + \theta_2 z_2(x) + \cdots + \theta_p z_p(x)) \qquad (1)$$

where $P_\theta(x)$, the probability of the modeled network being identical with the observed network, is a function of network configurations $z_k(x)$ weighted with their respective parameters θ_k. The normalizing term $k(\theta)$ ensures that the probability mass function adds up to one. It is given by:

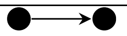
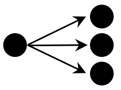
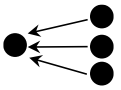
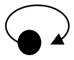
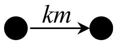
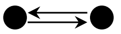
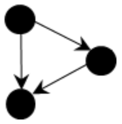
$$k(\theta) = \sum\nolimits_y \exp\left(\theta_1 z_1(y) + \theta_2 z_2(y) + \cdots + \theta_p z_p(y)\right) \qquad (2)$$

Basically, the exponential random graph model attempts to find parameters for each configuration in a way that maximizes the probability of the modeled network being identical with the observed one. For this process, a model with dyad-dependent terms relies on Markov Chain Monte Carlo (MCMC) maximum likelihood estimations. MCMC simulations generate a sample from the space of all possible networks to approximate θ_k. In an iterative process, the MCMC sample average statistics are compared with the observed statistics until differences are sufficiently small, leading to model convergence. However, for poor model specifications, MCMC simulations are not able to build networks that adequately represent the observed network (model degeneracy). Recently, Krivitsky (2012) proposed techniques to handle ERGMs with valued ties, i.e. valued ERGMs. These models rely on a reference distribution (e.g. Poisson), as the sample space for valued graphs without an a priori upper bound limit is infinite. Both model types, binary and valued, are used to study the regional patent licensing network.

4.3.4 Variables

Exponential random graph models allow the inclusion of variables (i.e. network configurations) at three levels: the node level, the tie level and general network structure variables. For directed networks, node-level variables can be modeled for both out-going and in-going links, allowing for a thorough and differentiated analysis of regional characteristics affecting innovation diffusion. Table 6 provides a brief overview and network illustrations of all important variables used to explore the network, while further details for each variable follow.

Table 6: Variable description for chapter four

Name	Description	Illustration	Level
EDGES	Number of links in the network		Structural
OUTDEGREE (out)	Number of out-going links per node (activity effect)		Node
INDEGREE (in)	Number of in-going links per node (popularity effect)		Node
LOOP (in/out)	Valued network loops		Node
SIZE (in/out)	Log population per region	●	Node
INVEST (in/out)	Total investments in treatment of environmental pollution	●	Node
FEE (in/out)	Total receipts from fees on waste discharges	●	Node
GEODIST	Geographic distance between two nodes		Tie
MUTUAL	Number of pairs of actors (reciprocated links)		Tie
GWESP	Geometrically weighted edgewise shared partner distribution, indicating triadic closure		Structural

Note that further structural variables such as degree distributions are omitted from this table as they are less relevant from a theoretical perspective and only serve methodological purposes. The node-level variables except for activity and popularity effects are modeled for both in-going and out-going links.

EDGES, a structural network variable, indicates the number of links in the network. It can be interpreted similarly to the intercept in a standard regression model and serves as a baseline propensity towards tie creation. Moreover, it supports modeling the network density. *OUTDEGREE* indicates the weighted number of outward links on the node level and captures activity effects. In more detail, for a source region (licensor region) this variable represents the number of linked target regions (licensee regions). In an analogous manner, *INDEGREE* indicates a region's number of inward links, illustrating popularity effects. *LOOP* captures the number of within-regional license agreements. This node-level variable reflects intra-regional innovation diffusion processes and thus indicates the regional technological coherence, i.e. the interconnectedness of local technology supply and demand.[24] Furthermore, *SIZE* controls for size effects and represents the regional log population derived from the Chinese census in 2010, which is assumed to be relatively stable over time. Two variables are employed to measure the impact of environmental regulations, which differ across regions. *INVEST* denotes the total investments in treatment of environmental pollution and *FEE* indicates the total receipts from fees on waste discharges.[25] The former measures regional environmentally friendly efforts, while the latter follows the rationale of a negative financial incentive. Both variables are included to account for regulatory mechanisms potentially triggering environmental innovation diffusion (Hojnik & Ruzzier, 2016; Rennings, 2000). Next, *GEODIST* is a tie-level variable which captures the geographic distance in kilometers between two regions. The geometries were retrieved from GADM to determine the prefectures' geographical centroids, which were then used to calculate a region-to-region distance matrix.[26] *MUTUAL* represents reciprocity in tie creation. That is to say, the variable describes the instance that a link between two regions is reciprocated, hence mutually linking the regions. Finally, *GWESP* is a structural variable used to model the distribution of geometrically weighted edgewise shared partners. The variable indicates triadic closure: with license agreements between region *A* and region *B*, and at the same time agreements between *A* and *C*, triadic closure would suggest that *B* also links with *C*.

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[24] Since ERGMs are not able to predict loops (i.e. links that connect a node to itself), including the number of within-regional licenses as an independent variable is possible.

[25] Data from the China Statistical Yearbook on Environment 2007. Data was collected on the provincial level and then disaggregated to the prefectural level using regional population shares. More recent data could not be retrieved, but the spatial patterns of environmental regulations did not change significantly over time in China (Ren et al., 2018).

[26] Great Circle (WGS84 ellipsoid) distance.

4.4 Results and discussion

4.4.1 Discussion of empirical results

Table 7 lists results of three fitted ERGMs. Model 4.1 is a binary specification with all node-level variables split into two effects, one for in-going links and one for out-going links. The refined model 4.2 is an adapted version of the full model, including the main significant factors only. Model 4.3 is a valued ERGM and includes main factors from model 4.2 as well as some further specifications for valued modeling techniques. All findings for the binary models are supported in the valued model. This implies that not only tie creation per se is associated with the variables discussed below, but also the strength of these ties.

Positive and significant coefficients for *OUTDEGREE* and *INDEGREE* point towards both network activity and network popularity effects. A region that is very active in out-licensing technology is more likely to establish further out-going linkages to other regions. At the same time, a popular region that already receives many in-going links (i.e. a region that in-licenses a lot), is likely to in-license even more. The activity effect is also related to the notion of the technological advantage of a lead market, influencing extra-regional diffusion processes. These results generally support the idea of regional lead markets, with one or a few regions being responsible for the diffusion of innovations. From a network perspective, the findings point towards an increasing degree centrality of already central regions and preferential attachment mechanisms, which was also observed in related studies (Yutao Sun & Grimes, 2017). A lead market might thus emerge in a region where both processes, in- and out-licensing, occur simultaneously. This region will drive the market formation for green technologies as it in-licenses a lot, while it will also significantly affect technology adoption in other regions via out-licensing.

Estimates for *LOOP* suggest that regions with high levels of intra-regional innovation diffusion link less with other regions, which holds true for in-licensing and out-licensing. In other words, the higher the number of intra-regional licensing processes, the lower the number of inter-regional licensing processes. This implies that regions with low levels of internal knowledge diffusion establish more links to other regions for providing and sourcing knowledge. This finding has important implications for theorizing about the technological advantage in the lead market literature (e.g. Quitzow et al., 2014). In order to establish a lead market and gain competitive advantage in a technology, demand for technologies in the lead market region must be similar to other regions, and technologies should not be too region-specific (Beise & Rennings, 2005b). Against this background, the strong interconnection of regional technology development and regional demand becomes evident (Dewald & Truffer, 2012; Losacker & Liefner, 2020b).

Apart from that, the models control for regional population, with positive estimates for *SIZE* underlining that more highly populated regions are associated with a higher number of knowledge diffusion processes, which is in line with the literature on the geography of innovation diffusion (Hägerstrand, 1967; Lengyel et al., 2020).

The positive estimate of *FEE* on out-licensing emphasizes the role of regulations for environmental innovation and lead market dynamics. Negative financial incentives such as high fees for waste discharge are positively associated with the out-licensing activity of a region, indicating that the technologies developed in this region are also useful for extra-regional organizations. Traditionally, the lead market framework suggests that extra-regional implementation of effective regulations and policies is needed to drive innovation diffusion (Beise & Rennings, 2005b). However, the empirical results in this study suggest that some regional regulatory effects might be sufficient to steer the diffusion of environmental innovations. This effect does not hold for in-going links, which implies that regions with strict regulations rely on local technologies. At the same time, the benefits of these local technologies seem to be anticipated by other regions, which becomes evident from the positive and significant estimate for out-going links. Moreover, *INVEST* reveals a negative effect on out-licensing. Regional investments in the treatment of environmental pollution do not lead to developing environmental innovations that are demanded in other regions. This suggests that such policies rather lead to developing region-specific technologies, which is also underpinned by the non-significant effect for in-going links. In summary, the findings reveal that the relationship between environmental regulation and diffusion of environmental innovations is very complex from a regional perspective. Some regulations might lead to the adoption of local technologies within the region, some might lead to the adoption of local technologies in other regions, and some might lead to the local adoption of technologies from other regions.

Table 7: *Results of exponential random graph models*

	(4.1) Full binary model		(4.2) Refined binary model		(4.3) Valued model	
	Coefficient	(SE)	Coefficient	(SE)	Coefficient	(SE)
EDGES	-12.140***	(0.028)	-12.170***	(0.039)	2.394***	(0.089)
OUTDEGREE	0.067***	(0.003)	0.067***	(0.003)	0.078***	(0.002)
INDEGREE	0.102***	(0.005)	0.102***	(0.005)	0.113***	(0.004)
LOOP (in)	-0.006***	(0.001)	-0.006***	(0.001)	-0.008***	(0.001)
LOOP (out)	-0.003***	(0.001)	-0.003***	(0.001)	-0.004***	(0.001)
SIZE (in)	0.188***	(0.043)	0.195***	(0.039)	0.382***	(0.041)
SIZE (out)	0.325***	(0.042)	0.320***	(0.039)	0.710***	(0.041)
INVEST (in)	-0.039	(0.138)				
INVEST (out)	-1.654***	(0.139)	-1.666***	(0.139)	-2.274***	(0.012)
FEE (in)	0.000	(0.000)				
FEE (out)	0.003***	(0.000)	0.003***	(0.000)	0.004***	(0.000)
GEODIST	-0.001***	(0.000)	-0.001***	(0.000)	-0.001***	(0.000)
MUTUAL	1.060***	(0.115)	1.062***	(0.113)	0.876***	(0.047)
GWESP (0.5 fixed)	0.188***	(0.051)	0.184***	(0.050)		
gwidegree(0.1 fixed)	-7.328***	(0.110)	-7.377***	(0.112)		
gwodegree(0.1 fixed)	-22.330***	(0.097)	-22.330***	(0.104)		
odegree(0)	-21.090***	(0.097)	-21.080***	(0.104)		
idegree(0)	-6.600***	(0.108)	-6.636***	(0.110)		
nonzero					-25.340***	(0.089)
AIC	10,415		10,414		-220,650	

Significance. ***p < 0.001, **p < 0.01, *p < 0.05

Note that the geometrically weighted out-degree and in-degree distribution with a decay parameter of 0.1 as well as a static effect for the number of nodes with zero out-degrees and in-degrees were added to assist model convergence in the binary models. *GWESP* is modeled using a decay parameter of 0.5. For the valued model, *EDGES* is corrected by a power of sum 0.5 to overcome overdispersion, and *MUTUAL* is of type minimum. A Poisson reference distribution was used for the valued model, with all node-level terms having the form non-zero. See Krivitsky (2012) for further information on all model specifications. All Models converged twice.

While it is widely acknowledged that regulatory measures affect both innovation development and innovation adoption in regions and countries (Hojnik & Ruzzier, 2016; Horbach, 2016), little is known about the implicit geography of such innovations (Herman & Xiang, 2019). If environmental regulations trigger innovation development, where are these innovations adopted? And if regulations promote the adoption of environmentally friendly technologies, where do they come from? Patent licensing data is obviously very useful to answer such questions in future research on the role of regulations for environmental innovation.

In addition to these node-level characteristics, some interesting effects on the tie level are unveiled. In more detail, *GEODIST* suggests that geographic distance between regions decreases the likelihood of concluding license agreements for green technologies. This supports the earlier finding that most license agreements are in fact concluded in the same region. Diffusion of green technologies thus seems to be limited to close geographic boundaries, which can be explained by the tacit nature of the knowledge involved, as green technologies are often very complex (Balland & Rigby, 2017; Barbieri, Marzucchi, et al., 2020). However, this also reflects the spatiality of sustainability transitions, as supply and demand of environmental innovations seem to be highly interlinked within limited geographic boundaries (T. Hansen & Coenen, 2015). Lead market formation might thus benefit from early adopter experience and technological legitimacy in geographically close places (Olson, 2018; Rohe & Chlebna, 2021).

Furthermore, results suggest that license agreements between two regions are reciprocated, as *MUTUAL* indicates a positive effect on tie creation. This is in line with previous work arguing that license agreements are often concluded between already established collaboration partners in known and trusted environments (Bidault & Fischer, 1994; Mendi, Moner-Colonques, & Sempere-Monerris, 2020; Seo & Sonn, 2019a), which can also be translated to the regional level. Innovation diffusion between regions is thus often symbiotic. Once a region provides knowledge to extra-regional partners, it is likely that it will also create positive in-going links for the region, increasing the regional technological capabilities. At the same time, this might imply that regions which are already closely linked to a lead market region via out-licensing are more likely to adopt innovations from the lead market than less linked regions.

Finally, the positive estimate for *GWESP* hints at triadic closure processes in the regional patent licensing network. This points to the complexity of innovation diffusion processes and emphasizes the need for network perspectives, as not only direct relations between two regions seem to matter for diffusion to take place, but also indirect relations within the overall network.

Altogether, all models properly converged twice, with MCMC sample statistics varying randomly and without serial correlation, resulting in a normal distribution of the difference between observed and modeled values for each variable. Trace plots and density plots for MCMC diagnostics of model one are provided in Figure A.5 in Appendix B. Moreover, the models reveal a high goodness-of-fit, as observed network properties such as edgewise shared partners, geodesic distances and degree distributions are adequately reproduced by the models (see Figure A.6 in Appendix B).

4.4.2 Robustness checks

In order to check robustness, the same model specifications were applied on several subsets of the network (see Table A.3 in Appendix B). Irrespective of important common features outlined in section 4.2.1, green technologies originate from different technological domains, address various sectors (see also Table A.2 in Appendix A), and diffusion might thus depend on different factors and processes (Haščič & Migotto, 2015). Therefore, subsets based on the two largest one-digit ENV-TECH domains were constructed: environmental management (domain one) and climate change mitigation technologies related to energy (domain four). In addition to that, the data set was split into two parts based on the median licensing date in order to check for heterogeneity over time. The models were thus estimated for a network based on all license agreements concluded before 2012-05-10 and for a network after that date. Most variables remain robust for these specifications, with only minor differences. That is to say, *LOOP* for out-going links is not significant in environmental management technologies, indicating that high levels of intra-regional licensing might not affect the likelihood of out-licensing in that domain. In addition, the non-significant effect of *INVEST* for in-going links holds neither for the technology-wise subsamples nor for the period one network. Instead, these models suggest a negative effect of regional investments in the treatment of environmental pollution on in-licensing green technologies. This might be due to the dependence on local technologies, and the effect is likely to lose significance over time because of data accuracy. *GWESP* is non-significant for domain four technologies, which can be explained by the small network size and density. Altogether, the main findings remain robust for several further specifications and subsets. As outlined in section 4.3.3, binary ERGMs are basically logistic regression models for specifications without dyad-dependent terms. Logistic regression models for all dyad-independent terms were thus employed for comparisons with ERGM results. All variables show similar results in these models. However, goodness-of-fit tests reveal that the observed network is poorly recreated based on those estimates. Edgewise-shared partners and degree distributions in particular are not in line between the modeled and the observed network. This highlights the value of exponential random graph modeling techniques when working with network data and supports the empirical approach of this study.

4.4.3 Limitations

The results presented are subject to some limitations. Licensing data for Chinese patents is limited to the fact that recording license agreements at CNIPA is not compulsory, excluding an unknown amount of non-recorded licensed patents from this study. Nonetheless, it is likely that a large share of license agreements are recorded, as both licensor and licensee benefit from the official record. That is to say, in case of infringement disputes or litigations, the recorded license agreement can serve as a basis for legal decisions. Additionally, governmental support for firms (i.e. subsidies) often depends on the condition that firms can prove that they hold intellectual property rights (also licenses). However, this might lead to a selection bias, as some firms might acquire low-cost licenses to receive a high-tech status without making use of the licensed technology. Such low-cost licenses are typically obtained from individuals and not from firms or research institutions (Yang et al., 2019). Moreover, there might be a bias in the geocoding process. Universities and research institutions are geocoded more precisely than firms, as they are most often located in one city only and have a distinct name.

Regional knowledge and innovation networks generally apply a functionalist perspective, treating regions as nodes, neglecting links within regions and supposing that links between two organizations from different regions connect all organizations between those regions (see also Figure 6). Wanzenböck (2018) recently introduced sophisticated techniques to overcome these shortcomings by including organization-level network structures in regional networks. These techniques, however, cannot be applied to the network in this paper, as organization-level data could not be harmonized, with name disambiguation not being possible in the Chinese context. The empirical approach in this paper provides a detailed analysis of prefecture-level data in China, while studies on license agreements usually need to refer to provinces due to lack of geocoding quality (e.g. Wang, Li-Ying, et al., 2015; Wang, Pan, et al., 2015; Yang et al., 2019; Zhang et al., 2016). While this is a strong advantage of the empirical part of this paper, it also leads to a shortcoming, as it was not possible to consider longitudinal models due to low network density in temporal networks and missing license agreement durations. Although the robustness checks in models 4.6 and 4.7 suggest that the temporal dimension might be less relevant for this paper (see Table A.3 in Appendix B), other studies have demonstrated the value of using temporal ERGMs (Broekel & Bednarz, 2018; D. Ma et al., 2021). All results need to be interpreted with the above-mentioned limitations in mind.

Finally, it is necessary to emphasize that this study considers only green technologies. While these technologies feature conceptual specificities (see section 4.2.1), it is unclear to what extent the results of this study apply exclusively to them. It is reasonable to assume that the general determinants of inter-regional diffusion in the licensing network are also valid for other types of technologies, whereas the environmental regulation factors should not be relevant for non-green technologies, at least from a theoretical perspective (Faber & Frenken, 2009; Hojnik & Ruzzier, 2016; Rennings, 2000). It appears likely that the diffusion of green technologies is much more dependent on local demand conditions and is more constrained geographically due to higher technological complexity (Barbieri, Marzucchi, et al., 2020). However, further research is needed to empirically identify differences and similarities between green and non-green technology diffusion in this regard. It should also be noted that patents do not cover the entire range of environmental innovations, and that other means of diffusion besides licensing exist.

4.5 Conclusion

This paper has uncovered important regional and network-specific characteristics that explain the inter-regional diffusion patterns of green technologies, linking to the scholarly discussions on regional lead markets and the geography of sustainability transitions. For this purpose, a regional patent licensing network for green technologies in China was constructed and analyzed using exponential random graph models. Findings show that most patents are licensed within a region and that geographic proximity matters for inter-regional licensing. Moreover, network activity and network popularity effects imply that a small number of regions are responsible for the diffusion of green technologies, which is in line with the conceptualization of regional lead markets by Losacker and Liefner (2020). The results also point towards the importance of region-specific technologies. Some regions strongly rely on locally developed technologies and thus link less with other regions, while some regions develop technologies that find commercial application in extra-regional markets.

In that regard, regulatory measures are likely to play an important role and need the attention of future conceptual and empirical studies: regulations that create local demand for green solutions trigger innovation diffusion across regions, whereas regulations that strengthen the local producers seem to decrease the likelihood of extra-regional diffusion. This result is also crucial for both environmental policy and innovation policy. Regulations have usually been indistinctively associated with increasing development and adoption of green technologies (Hojnik & Ruzzier, 2016). However, the results of this study suggest that this view is too simplistic, as positive effects of supply-oriented regulations may be limited to the respective administrative regions. Effective policies and regulations should thus be designed in a way that locally developed technologies are also useful for further regional markets and do not remain in local niches, and demand-oriented measures seem to be the favorable approach (Hansmeier & Losacker, 2021; Tödtling et al., 2021). Apart from that, results suggest that innovation diffusion between two regions is symbiotic, as license agreements are often reciprocated. The spatial diffusion of green technologies, however, relies not only on regional characteristics and inter-regional relations, but also on more complex network processes such as triadic closure.

These findings are important for both academia and policymakers. Firstly, the findings support the recent calls for more space-sensitivity (Binz et al., 2020) and methodological diversity (Hansmeier et al., 2021) in research on environmental innovation and sustainability transitions. A regional perspective on lead markets is also supported, as diffusion processes appear to take off from highly active regions. At the same time, the paper finds evidence that innovation diffusion takes place within close geographic boundaries. This emphasizes the role of regional technological capabilities for lead market formation. However, these technological capabilities should not be too region-specific and account for demand preferences in other regions. The paper thus complements recent research by Losacker and Liefner (2020) on regional lead market formation and adds empirical evidence on the next stage in the lead market concept, the actual spatial diffusion of innovations. Network perspectives seem to prove useful in that respect and should thus be applied more often, as regular econometric models neglect dependencies between actors or regions. The paper also promotes the usefulness of newly available data such as license agreements, increasing the validity of indicators in empirical research. In particular when measuring technological innovation, empirical studies often overestimate the explanatory power of regular patent data, with statistics often being artificially inflated. Licensed patents, in contrast, are more appropriate for measuring innovations, as they reflect actual market utilization and economic value. In addition, license data has proven to be a very helpful indicator for innovation diffusion in this paper, as it allows the localization of both innovation development and innovation adoption. From a methodological perspective, the paper contributes to recent sophisticated efforts towards geocoding patent data (e.g. Perruchas et al., 2020) and especially patent licensing data (e.g. Yang et al., 2019). Secondly, regional policymakers who aim to increase a region's competitive advantage in green technologies should consider an appropriate policy mix, as innovation diffusion is not solely a matter of innovation policy, with environmental regulations often playing an important role for the adoption of green technologies. Moreover, in order to establish a regional competitive advantage following the lead market rationale, regional technology development should incorporate foreign demand preferences. Sourcing extra-regional knowledge should also not be interpreted as a sign of lacking resources, as this might lead to a reciprocal technology transfer and symbiotic benefits. Further research is needed in the following regards. This paper unveils the geography of green technology diffusion on a general level. Future studies need to take technology-specific factors into account, focusing on one particular technology only. Moreover, the diffusion of green technologies and environmental innovation is likely to also depend on lead market factors which were not considered in this study, i.e. transfer advantages, export advantages or price advantages. More empirical research is needed that accounts for several lead market factors, particularly different types of regulations, to support case study findings on the different lead market factors (Horbach et al., 2014; Quitzow et al., 2014; Zubaryeva, Thiel, Barbone, & Mercier, 2012). As network perspectives can add great value to the existing knowledge on innovation diffusion, similar methodologies should be used more often, especially in the literature on environmental innovation and sustainability transitions. Finally, since patent license agreement data has proven to be a valuable indicator to measure innovation diffusion, great efforts will be required to make this kind of data more accessible for analyzing countries other than China, enabling the exploration of the international diffusion patterns discussed in the lead market literature.

CHAPTER FIVE

Geography and the Speed of Green Technology Diffusion

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Abstract

A fast adoption and diffusion of green technologies will be essential for a successful transition of the world's economies towards more sustainable modes of production and consumption. This article investigates the speed of green technology diffusion in China using a unique data set, which lists geocoded patent license agreements for green technologies from 2000-2019. We focus on the relation between spatial determinants, including geographic proximity and regional technological specialization, and the time-to-adoption, thus analyzing the factors explaining the time between technology development (patent application) and technology adoption (licensing). The main finding is that geographic proximity to the innovator is associated with an accelerated time-to-adoption. Moreover, we find that the more a region specializes in green technologies, the faster a patent is licensed within that region.

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5.1 Introduction

In order to mitigate climate change and other environmental concerns, the world's economies need to shift towards cleaner and more sustainable modes of production and consumption. This socio-technical transition will require the development and use of environmental innovations, i.e. green technologies, to replace conventional and environmentally harmful technologies. The transition needs to happen quickly and overcome the many factors that account for a persistence of established technological regimes, underlining the need for a fast adoption and diffusion of green technologies (Markard et al., 2020; Wilson et al., 2020).

There is a general consensus that firm-level characteristics, demand-pull, supply-push and regulatory factors play an important role for environmental innovation adoption in firms (Barbieri et al., 2016; Hojnik & Ruzzier, 2016; Horbach, 2008; Horbach et al., 2013), with regional characteristics and knowledge spillovers also affecting adoption rates (Antonioli et al., 2016; Horbach & Rammer, 2018). In that regard, the evolving literature on the geography of innovations and sustainability transitions emphasizes the importance of spatial proximity and place specificities for green technology diffusion, as markets for technologies emerge close to their origin (Dewald & Truffer, 2011, 2012; T. Hansen & Coenen, 2015; Losacker & Liefner, 2020b). While this literature has significantly contributed to understanding the spatiality of green technology diffusion as well as to corresponding regional patterns, there has been little discussion so far about the role of geography for the *speed* of green technology diffusion.

Previous research suggests that innovations diffuse faster within geographical clusters and that early diffusion occurs mainly between large agglomerations (Baptista, 2000, 2001; Hägerstrand, 1967; Lengyel et al., 2020). At the same time, environmental innovations need stringent regulations to be adopted (Beise & Rennings, 2005b; Rennings, 2000) and they tend to diffuse comparatively slowly due to their high technological complexity (Barbieri, Marzucchi, et al., 2020; Wilson et al., 2020). These rather general observations, however, leave much uncertainty about how region-specific factors influence and potentially accelerate the adoption of green technologies. Put simply, we know very little about how geography matters for the speed of green technology diffusion.

This article aims to fill this gap and to provide empirical insights on the – spatial and non-spatial – drivers of the speed of green technology adoption. We make use of a unique data set, which lists geocoded patent licensing agreements of green technologies in China to analyze the determinants explaining the time between innovation development (patent application) and innovation adoption (licensing). Since we consider licensing agreements for patents as an indicator for innovations taken to the diffusion stage, we explicitly focus on the early diffusion phase, i.e. the first adoption of an innovation. For the empirical part of this article, we use survival models and distinguish between different patent types as well as between inter-regional and intra-regional diffusion processes.

The remainder of the paper is organized as follows. Section 5.2 summarizes the theoretical foundations and reviews relevant literature, which translates into the formulation of research propositions. Section 5.3 presents the empirical approach, data and methods that lead to the results discussed in section 5.4. Section 5.5 summarizes main results and offers policy recommendations.

5.2 Literature review and theoretical foundations

5.2.1 Environmental innovations and green technologies in China

Environmental innovations are crucial for addressing societal challenges such as environmental pollution, resource scarcity, waste management and climate change. In accordance with a comprehensive definition by Kemp & Pearson (2007, p. 7), these innovations are environmentally benign subsets of all innovation activities: '*Eco-innovation is the production, assimilation or exploitation of a product, production process, service or management or business method that is novel to the organisation (developing or adopting it) and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives.*' In this article, we focus on technological environmental innovations, i.e. green technologies, which we use as synonymous terms.

Over the past two decades, a rich body of literature has emerged examining the development and diffusion of environmental innovations (Barbieri et al., 2016; Hojnik & Ruzzier, 2016). The scholarly interest in environmental innovations, however, is not only rooted in the societal relevance of these types of innovations, but also in some specific peculiarities that distinguish them from regular innovations, both from a theoretical and an empirical perspective. That is to say, environmental innovations suffer from additional externalities in the diffusion phase (double externality problem), as adopters need to internalize costs of reducing global environmental harms. This market failure leads to the need for a regulatory fix (Jaffe, Newell, & Stavins, 2005; Rennings, 2000). In accordance with the famous Porter hypothesis, environmental regulations may also increase the competitiveness of firms through their triggering effect on innovation, thus leading to a win-win situation for the economy and the environment (Porter & van der Linde, 1995). Empirical research on environmental innovations and green technologies suggests that they tend to be more complex and have a stronger impact on future technological developments (Barbieri, Marzucchi, et al., 2020; Horbach et al., 2013). They also seem to rely to a greater extent on R&D collaborations and external knowledge compared to other technological innovations, to name a few peculiarities (De Marchi, 2012; Ghisetti et al., 2015).

With most green technologies still in the early stages of the technology life cycle, green windows of opportunity are opening up, especially for emerging economies, to take international leadership and to become lead markets (Lema et al., 2021). Against this background, China is a particularly interesting case because, on the one hand, it is responsible for a major share of current annual greenhouse gas emissions, but on the other hand, it is also a leading supplier of many green technologies, such as solar PV (Ely et al., 2019). In this context, however, China not only engages in manufacturing, but also leads the technological frontier in many fields, shaping global socio-technical regimes (Gosens et al., 2020; Walz et al., 2017). The Chinese government is strongly pushing its leading role in green technologies, which is reflected in the current and past 5-year plans.

From an economic geography perspective, however, regional disparities in terms of technological capabilities and market characteristics are very pronounced in China (Kroll & Neuhäusler, 2020), and political aims in terms of promoting green technologies vary considerably on the local scale (Brehm & Svensson, 2020). Chinese regions are thus very heterogeneous, with local governments and local industrial specializations leading to different regional trajectories as well as complex interdependencies between regions (Losacker & Liefner, 2020b). It is unclear how the diffusion of environmental innovations in China is organized geographically and, in particular, what (spatial) logic determines the early adoption of such innovations.

5.2.2 The speed of green technology adoption: general determinants

Studying the diffusion of innovations has a long history in innovation studies, dating back to pioneering work by Rogers (1962), who defined different groups of adopters based on the speed of adoption. In that regard, early adopters are of particular importance as they mainstream the diffusion process while also providing early user-feedback, which is necessary for subsequent technological progress.

The diffusion process as well as the time to the first adoption of (environmental) innovations can be expected theoretically to depend on a number of general factors relating to the invention itself and the supplier (technology push), the adopter (demand pull) and the regulatory context (regulatory push/pull) (Fichter & Clausen, 2021; Hojnik & Ruzzier, 2016). Firstly, characteristics inherent to the technology and the invention determine the speed of adoption. The quality of the invention has a decisive impact on how quickly it will be adopted, while inventions that have a broad application base and are therefore relevant for a large market will also diffuse more easily (H. Lee, Smith, & Grimm, 2003). In contrast, complex inventions are likely to diffuse slowly due to increased efforts in translating them into viable innovations (Wilson et al., 2020). Secondly, the capabilities of the innovator play an essential role for the time it takes for an invention to be brought to market (R. Ma, Zhu, & Liu, 2021), with firms being generally more efficient in commercializing technologies than universities (Markman, Gianiodis, Phan, & Balkin, 2005; McCarthy & Ruckman, 2017) and some innovators lacking skills to find appropriate technology users (Kani & Motohashi, 2012). Thirdly, the capabilities of potential adopters matter in terms of how well they can anticipate the potential use of an invention (Laursen, Leone, & Torrisi, 2010), and, of course, the various motives for adoption play an important role (Bergek & Mignon, 2017; Corrocher & Solito, 2017). While these mechanisms do not necessarily apply specifically to environmental innovations, the regulatory push/pull does. In fact, the regulatory setting and environmental policies strongly influence the diffusion process of environmental innovations, with stringent regulations favoring early adoption (Popp, 2010). Previous studies on green technology diffusion have mainly focused on international dynamics, in particular due to the role of national policies and data availability, leaving much uncertainty about the actual role of geography beyond factors relating to the nation state (Dechezleprêtre, Glachant, Haščič, Johnstone, & Ménière, 2011; Dechezleprêtre, Glachant, & Ménière, 2013).

5.2.3 The speed of green technology adoption: the role of geography

From a spatial perspective, research suggests that the speed of adoption is dependent on geographic proximity to the innovator, that innovations diffuse faster within geographical clusters and that early diffusion occurs mainly between large agglomerations (Baptista, 2000, 2001; Hägerstrand, 1967; Lengyel et al., 2020). For environmental innovations, the assumption by which the speed of adoption depends on spatial proximity to the innovator is supported by additional considerations. That is to say, the development of environmental innovations requires diverse knowledge as well as unique combinations of many technological components (Barbieri, Marzucchi, et al., 2020). This is reflected in high degrees of R&D cooperation, external knowledge and team efforts needed for the development of environmental innovations (De Marchi, 2012; Ghisetti et al., 2015; Horbach et al., 2013; Orsatti, Quatraro, et al., 2020). For these reasons, environmental innovations specifically benefit from regional knowledge spillover effects stemming from co-located inventors as well as spatial proximity to universities and research institutes (Horbach, 2014; Quatraro & Scandura, 2019). The above-mentioned ingredients needed for the development of environmental innovations may lead to the formation of regional innovation networks and the integration of users in innovation processes, making it likely that early adopters are located close to innovators.

The essential conclusion from the emerging literature on peculiarities of green technologies and environmental innovations is that they involve diverse technological inputs marking them as technologically complex (Barbieri, Marzucchi, et al., 2020). As knowledge involved in complex technologies tends to be spatially sticky (Balland & Rigby, 2017), the diffusion of environmental innovations is geographically confined, which is particularly relevant for early adopters. Apart from that, the initial stages of market formations are highly localized, with pioneering users often being located close to where innovation development takes place (Dewald & Truffer, 2011, 2012). These considerations lead to a first proposition:

P1: *Geographic proximity to the innovator is associated with an accelerated time-to-adoption of environmental innovations.*

However, the role of geography for the speed of green technology diffusion is not limited to the dependence on distance. In fact, the role of geography may well be more complex, which results from a couple of further arguments. The double-externality problem implies that regulations strongly affect the diffusion of environmental innovations (Rennings, 2000). Differing regulatory settings at the regional level thus lead to corresponding spatial patterns of innovation emergence and adoption. Moreover, the geographic agglomeration of pioneering firms that have adopted environmental innovations can create a positive spillover effect on other firms, influencing the probability that these firms will also turn to greener technologies (Antonioli et al., 2016; Cainelli, Mazzanti, & Montresor, 2012). This is particularly caused by demonstration effects that early adopters exert on others, marking them as regional role models. Intra-regional exchange of experiences and knowledge support this process. For potential new adopters, learning and awareness effects arise that might accelerate the diffusion of environmental innovations (Baptista, 2001; Graziano & Gillingham, 2015; Horbach & Rammer, 2018).

P2a: *Time-to-adoption of environmental innovations is accelerated if other environmental innovation adopters are located in the adopter's region.*

Similar effects can also occur on the innovator's side. An innovator will be able to learn from other innovators in the region (Asheim & Gertler, 2005; Fosfuri, 2006), allowing faster time to commercialization.

P2b: *Time-to-adoption of environmental innovations is accelerated if other environmental innovators are located in the innovator’s region.*

Apart from these processes, the emergence and adoption of environmental innovations are highly place-specific and depend on various regional factors, such as regional institutions or technological specialization (T. Hansen & Coenen, 2015). If a region specializes in green technologies, it will increase the likelihood of developing and adopting further green technologies as a result of accumulated knowledge and resources (Grillitsch & Hansen, 2019; Montresor & Quatraro, 2020). In light of this, it appears that innovators in regions that specialize in green technologies are able to commercialize innovations more quickly. At the same time, we can assume that environmental innovations will also be adopted more quickly in these regions.

P3a: *Time-to-adoption of environmental innovations is accelerated if the adopter is located in a region that specializes in green technologies.*

P3b: *Time-to-adoption of environmental innovations is accelerated if the innovator is located in a region that specializes in green technologies.*

In essence, region-specific effects stemming from regional demonstrations and learning as well as from regional green specializations can be assumed to occur both in the innovator's region and in the adopter's region. In the case of inter-regional diffusion, regional supply-push factors and regional demand-pull factors hence take effect for two distinct regions. For the case of intra-regional diffusion, however, these effects arise simultaneously within one focal region. A discussion of how these scenarios and propositions can be operationalized empirically follows in Sections 5.3 and 5.4, as does a description of all important (control) variables that emerge from the theoretical arguments presented above.

5.3 Data and methodology

5.3.1 Using patent licensing data to measure innovation diffusion

Rapid technological progress as well as formalized intellectual property right systems have led to the emergence of a market for technologies, with license agreements being important means of transaction (Arora & Fosfuri, 2003; Gambardella, Giuri, & Luzzi, 2007; Kani & Motohashi, 2012). A large body of literature about the market for technologies has evolved, mainly aiming to understand motives of licensing as well licensing determinants and outcomes (e.g. Lee et al., 2017; Motohashi, 2008; Ruckman and McCarthy, 2017). In a license agreement, the technology developer and owner (the licensor) authorizes another organization (the licensee) to make use of a patented technology for commercial purposes. On the supply side, licensors seek to license out their technologies if possible revenue effects are higher than rent dissipation effects caused by new competitors (Arora & Fosfuri, 2003). On the demand side, licensees seek to license in technologies that they aim to make use of, indirectly outsourcing R&D activities.

Patent licensing is a localized phenomenon with licensors and licensees often residing within close geographic proximity (Losacker, 2020). A reason for that is the imperfect codification of tacit knowledge. Firms seek to acquire technology from their regional environment to allow for knowledge exchange with the inventors, as long-distance communications and patent documents might not capture the full know-how needed to make use of a technology (Mowery & Ziedonis, 2015). In addition, concluding a license agreement is a way to build long-term networks (Nelson, 2009), while networks and established relations to well-trusted partners in the region are often prerequisites for firms to conclude licensing contracts, limiting the risk of opportunistic behavior among partners (Bidault & Fischer, 1994; Seo & Sonn, 2019a).

From an empirical perspective, license agreements are a valuable indicator to measure market-mediated knowledge transfer. More importantly, however, they can be used to map innovation diffusion across time and space. Licensed patents represent actual innovations rather than inventions when compared to non-licensed patents because of their economic exploitation. Of course, however, patents that are used internally by the patenting firms are to be labeled innovations as well, but cannot be examined here. License agreements contain spatial and temporal information on both innovation development (licensor) and innovation adoption (licensee), highlighting their value for studying the early diffusion of innovations (Nelson, 2009).

Licensing data is often undisclosed and difficult to obtain, limiting research to the study of single licensors (e.g. Buenstorf and Schacht, 2013) or requiring large-scale surveys for data collection (e.g. Kani and Motohashi, 2012; Lee et al., 2017). Fortunately, these limitations do not hold in the Chinese context. Since 2008, the Chinese Patent Office (CNIPA) has endorsed a formal registration of license agreements and discloses information on all registered agreements. An official recording at CNIPA can be useful for licensors in legal disputes, while licensees benefit from the recording due to receiving a high-tech status for owing intellectual property, which is often necessary when applying for subsidies. By the end of 2019, more than 120,000 license agreements for Chinese patents had been officially recorded at CNIPA, of which about 10 percent were for green technologies.

For the empirical part of this article, we make use of the novel IncoPat patent database (www.incopat.com) that matches all recorded license agreements from CNIPA to the respective patent documents. We collected all licensed Chinese patents with commencement dates from 2000 to 2019, excluding design patents. In the next step, we filtered green technologies using the ENV-TECH classification (see Table A.2 in Appendix A for a comprehensive list; Table 8 provides an overview), which is standard in the field (Barbieri, Marzucchi, et al., 2020; Perruchas et al., 2020). The ENV-TECH classification links IPC and CPC classes to 8 different technological domains, 36 subgroups and 95 technologies. In an attempt to map the locations of licensors and licensees, we applied different geocoding strategies. For licensor locations, we filtered all patents where the patent applicant is also listed as the patentee, since the patentee is usually the registered licensor of the patented technology. This held true for about 85 percent of all patents. Next, we geocoded the applicant's address stated in the patent document using the GeoNames database (www.geonames.org). For licensees, however, neither patent nor license agreement provide geographical information. We thus made use of automated web search queries for licensee names using APIs from Google Maps and Baidu Maps, which enabled us to retrieve locations for about 90 percent of the licensees (mostly firms). After cross-checking results between Google and Baidu and several manual checks, our final data set contains 8954 license agreements for green technology patents with locations for licensors and licensees at the prefectural level.

Table 8: ENV-TECH classification of environment-related technologies (Haščič and Migotto, 2015)

Domain	Technological subgroups
Environmental Management	Air pollution abatement, water pollution abatement, waste management, soil remediation, environmental monitoring
Water-related adaptation technologies	Demand-side technologies (water conservation), supply-side technologies (water availability)
Climate change mitigation (energy)	Renewable energy generation, energy generation from fuels of non-fossil origin, combustion technologies with mitigation potential, nuclear energy, efficiency in electrical power generation, transmission or distribution, enabling technologies in energy sector, other energy conversion or management systems reducing GHG emissions
Capture, storage, sequestration or disposal of greenhouse gases	CO_2 capture or storage (CCS), capture or disposal of greenhouse gases other than carbon dioxide (N_2O, CH_4, PFC, HFC, SF_6)
Climate change mitigation (transportation)	Road transport, rail transport, air transport, maritime or waterways transport, enabling technologies in transport
Climate change mitigation (buildings)	Integration of renewable energy sources in buildings, energy efficiency in buildings, architectural or constructional elements improving the thermal performance of buildings, enabling technologies in buildings
Climate change mitigation (wastewater treatment or waste management)	Wastewater treatment, solid waste management, enabling technologies or technologies with a potential or indirect contribution to GHG emissions mitigation
Climate change mitigation (production or processing of goods)	Technologies related to metal processing, technologies relating to chemical industry, technologies relating to oil refining and petrochemical industry, technologies relating to the processing of minerals, technologies relating to agriculture, livestock or agroalimentary industries, technologies in the production process for final industrial or consumer products, climate change mitigation technologies for sector-wide applications, enabling technologies with a potential contribution to GHG emissions mitigation

5.3.2 Variables

Our unique data set allows us to study the speed of patent licensing, which we use as a proxy for the speed of innovation adoption. The dependent variable *speed* thus indicates the duration (in days) between patent application and patent licensing (similar to McCarthy and Ruckman, 2017). Given that we hold information on locations of both licensors and licensees, we can build variables not only at the patent-licensing level, but also at the regional level, which we can match to either the licensor or the licensee side.

A core variable of interest in this article is the geographic distance between licensor and licensee, which we measure in two different ways. On the one hand, we calculate the great circle distance for each region-to-region pair, using the prefectures' geographical centroids (*dist*). On the other hand, we build co-location dummies indicating whether licensor and licensee are located in the same prefecture (*intra_pref*) or province (*intra_prov*). We add a couple of important variables on the patent-licensing level that are likely to affect the time between patent application and licensing, following the reasoning from section 5.2 and related studies (McCarthy & Ruckman, 2017). The number of 4-digit IPC classes (*ipc*) reflects a patent's technological scope, while the number of claims listed on the patent (*claims*) captures the technological breadth and complexity. We include the average number of forward citations per year (*fwd_cit*) to control for patent quality, and we add a categorical variable that controls for the type of applicant, distinguishing between firms (*firm*, reference group), universities or research institutes (*uni*) and individuals (*indiv*). Finally, we add a dummy to indicate exclusive rights in a licensing agreement (*excl*) and a dummy to distinguish between utility model patents and invention patents (*util*). Green technologies, of course, do not form a homogenous group, so we add dummies for each ENV-TECH domain to take into account technology-specific heterogeneity. We also control for unobservable effects of licensing patterns over time by including dummies that indicate the year of licensing.

A further set of variables is constructed on the regional level. Based on the reviewed literature in section 5.2, we assume that regional learning effects and knowledge spillovers affect the time-to-adoption of green technologies. Accordingly, we construct a variable *green_lic_in* that captures the number of previous green licensees in a region. In other words, this variable reflects the number of green patents that have been licensed in to a region, which might give rise to learning effects on the demand side. In a similar way, we construct a variable *green_lic_out*, capturing the number of previous green licensors in a region, i.e. the number of green patents that have been licensed out from a region. This variable indicates learning effects on the supply side. Next, we calculated the relative patent activity (*rpa*) to measure the specialization of regions in green technologies (Horbach et al., 2014; Walz & Köhler, 2014). The *rpa* is normalized between -100 and 100 with positive values indicating a high specialization. It is based on the number of licensed patents p in technology j (green vs. non-green) and region r, and is given by:

$$RPA_{rj} = 100 \times \tanh \ln \left[\frac{p_{rj} / \sum_{r} p_{rj}}{\sum_{j} p_{rj} / \sum_{rj} p_{rj}} \right] \tag{3}$$

In addition, we account for the innovation capabilities of a region by including the number of non-green regional patent applications that have been licensed (*inno*). For all patent-based regional variables, we consider patents/licenses from the past three years before each licensing event. However, we also employed other time spans (2-5 years) as robustness checks, which we discuss in section 5.4.4 and Appendix A. In order to control for regions' size and agglomeration effects, we include the log regional population and population density (*pop*, *pop_dens*), derived from the Chinese census in 2010. Finally, we consider regional environmental regulations by adding a dummy *eco_reg*. The dummy indicates whether the prefecture is listed as a 'key environmental protection model' by the Chinese Ministry of Environmental Protection in the year of licensing. These regions need to complete pollutant control tasks and show high environmental performances to be listed, while they also serve to demonstrate benefits of environmental innovations (Brehm & Svensson, 2020). Descriptive statistics for all variables are provided in Table 9.

Table 9: Description of variables and descriptive statistics for chapter five

Variable	Description	Mean	SD	Min	Max
Dependent variable					
speed	Duration (in days) between patent application and patent licensing	1075.71	711.58	12	5573
Independent variables (patent-licensing level)					
dist	Geographic distance between licensor and licensee (in 100 km, based on prefecture-centroids)	2.73	5.08	0	35.45
intra_pref	Intra-regional licensing with licensor and licensee being located in the same prefecture (1 if yes)	0.6		0	1
intra_prov	Intra-regional licensing with licensor and licensee being located in the same province (1 if yes)	0.74		0	1
ipc	Number of IPC classes	2.49	1.63	1	24
claims	Number of claims	5.04	3.51	1	70
fwd_cit	Average number of forward citations per year	0.33	0.55	0	12.8
indiv	Applicant is an individual (1 if yes, ref. firm)	0.45		0	1
uni	Applicant is a university (1 if yes, ref. firm)	0.20		0	1
excl	Exclusive license agreement (1 if yes)	0.87		0	1
util	Patent is a utility model (1 if yes)	0.61		0	1
Independent variables (regional level)					
green_lic_in	Number of green licensees in the region in the last three years (in 100 patents)	0.52	0.71	0	2.89
green_lic_out	Number of green licensors in the region in the last three years (in 100 patents)	0.67	0.90	0	3.80
inno	Number of non-green innovations (licensed-out patents) in the last three years (in 100 patents)	7.41	7.39	0	29.12
rpa	Specialization in green technologies based on patents in the last three years (regional patent activity)	8.59	29.41	-84.59	95.99
eco_reg	Prefecture is listed as key environmental protection model city in year of licensing (1 if yes)	0.59		0	1
pop	Log population	15.10	0.69	12.85	17.17
pop_dens	Log population per km^2	5.79	1.01	0.56	8.59

Note: Reported statistics for regional variables are based on licensor regions (n = 258)

5.3.3 Estimation strategy

In order to explain the time required for a green patent to be licensed, we draw on survival modeling techniques, as they are particularly useful when estimating the time that elapses before an event occurs. The survival function is of key importance in this context, indicating the probability of surviving beyond time t. In this article, survival refers to the situation in which a patent is not (yet) licensed. A simple survival function can be written as follows with T denoting the time a patent is licensed.

$$S(t) = \Pr(T > t) \tag{4}$$

In a first step, we use non-parametric Kaplan-Meier estimations to model the survival function from our licensing duration data. The Kaplan-Meier estimator is given by:

$$\hat{S}(t) = \prod\nolimits_{T<t} (\tfrac{N_T - D_T}{N_T}) \tag{5}$$

where N_T is the number of patents that are not licensed at time T and D_T is the number of licensed patents at time T. This allows us to compare survival curves according to categorical variables, and to check for significant differences using log-rank tests. In a second step, we estimate the net effects of different variables on the acceleration or deceleration of time before a patent is licensed using parametric survival models. These models rely on the hazard rate λ, which describes the probability that a patent is licensed at time t, conditional on not being licensed before. The hazard function can be derived from $S(t)$ and its probability density function $f(t)$.

$$\lambda(t) = \frac{f(t)}{S(t)} \tag{6}$$

For this study, we assume that the hazard rate for licensing a patent is not uniform over time, with the hazard function following an arc-shaped distribution. Once a patent is applied for, the hazard of licensing increases over time due to ongoing search processes on the market for technologies and the time it takes to conclude an agreement. However, after some time, the hazard rate decreases again as the technology becomes less marketable and new technologies emerge (depreciation of innovations). Accordingly, there is a point in time at which the probability of licensing is highest. We test this assumption by comparing the kernel density estimates of the empirical hazard distribution with intercept-only models of several probability distributions, pointing to lognormal and generalized gamma distributions showing the best fit with our data. For the empirical part of this article, we thus employ parametric survival models with a lognormal distribution, which we estimate in an accelerated-failure-time (AFT) metric:

$$\ln(T_i) = \beta_0 + \beta_1 x_1 + \cdots + \beta_p x_p + \sigma \varepsilon_i \tag{7}$$

where $\ln(T_i)$ denotes the transformed survival time, β_0 denotes the intercept, $x_1 + \cdots + x_p$ represent the independent variables on the patent (and regional) level, $\beta_1 + \cdots + \beta_p$ are the corresponding coefficients, σ denotes the scale parameter of the lognormal distribution, and ε_i is the error term. In models that include regional variables, we add a shared frailty term α_r following a gamma distribution that captures unobserved heterogeneity at the regional level r.

5.4 Results and discussion

5.4.1 Effects of distance on time-to-adoption

Figure 8 shows Kaplan-Meier survival estimates, stratified into inter-regional and intra-regional license agreements. It provides an initial illustration of the fact that patents are licensed more rapidly in cases where the licensor and licensee are located in the same region (prefecture). In fact, intra-regional license agreements have a median time-to-licensing of 845 days and inter-regional licenses have a median time of 1017 days, which is a statistically significant difference (log rank test, $p < 0.001$). In the next step, we explore the effect of geographic distance on the speed of licensing, whilst controlling for additional factors that are not taken into account in the Kaplan-Meier estimates. Accordingly, Table 10 presents results of accelerated failure time models involving variables at the patent-licensing level. In the accelerated failure time metric, negative (positive) coefficients indicate an accelerating (decelerating) effect on the time between patent application and licensing. The natural exponent of a coefficient denotes the acceleration factor (i.e. time ratio), with values lower (higher) than one implying that time-to-licensing is shortened (prolonged).

We use all patents for model 5.1a, and split the data set into utility models and inventions for models 5.1b and 5.1c.[27] The goodness-of-fit is considerably better when modeling utility models and invention patents separately, owing to differing technological properties. Nonetheless, all models point to the fact that geographic distance (proximity) decelerates (accelerates) the time-to-adoption of green technologies (P1).

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[27] Utility models and invention patents are different legal types of patents in the Chinese intellectual property rights system. Utility models have a shorter term (10 years) and often involve technologies with shorter life cycles.

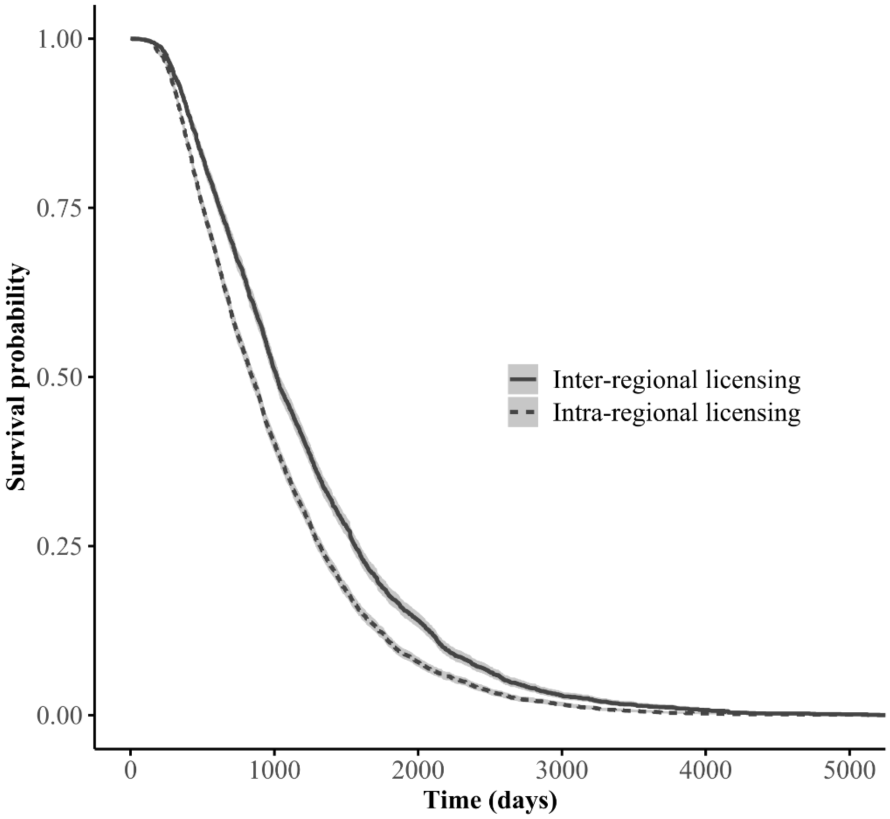

Figure 8: Kaplan-Meier survival estimates, stratified into inter-regional and intra-regional license agreements

To substantiate these results, we use co-location dummies as alternative indicators for geographic proximity in models 5.2a to 5.3b, denoting whether licensor and licensee are based in the same prefecture or province. These models also support the proposition that geographic proximity is highly relevant for the early adoption of environmental innovations, both for invention patents and for utility models. In more detail, we find that time-to-licensing changes by a factor of 0.9631 ($e^{-0.0376}$, $p < 0.001$) for utility models where the licensor and licensee are located in the same prefecture compared to licensor-licensee pairs that are not co-located. For inventions patents, we find an acceleration factor of 0.9195 ($e^{-0.0839}$, $p < 0.001$) for intra-regional license agreements relative to inter-regional license agreements. The effect of geographic proximity on time-to-licensing is thus substantial, with intra-regional license agreements for inventions (utility models) happening 8.05% (3.69%) faster than inter-regional license agreements. When considering licensing within provincial boundaries, effect sizes are even larger, with acceleration factors of 0.9323 ($e^{-0.0701}$, $p < 0.001$) for utility models and 0.9017 ($e^{-0.1035}$, $p < 0.001$) for invention patents. In summary, we find empirical evidence of a strong distance-decay of the speed of green technology adoption, supporting P1. This result is in line with existing research on innovation diffusion and underpins the arguments on the relevance of geography for the analysis of environmental innovations presented in section 5.2.

With regard to the controls, important differences between utility models and invention patents can be observed. For utility models, the results reveal that the number of IPC classes tends to have an accelerating effect on the time before it is licensed. A broad field of application thus leads to faster market entry. In other words, a technology that can be used in many areas will be adopted more quickly. In contrast, a high technological quality, indicated through the number of annual forward citations, is associated with a slower time-to-adoption. It will take longer on the market for technologies to assess the value of high-quality utility models, while concluding license agreements for valuable technologies also requires additional time (McCarthy & Ruckman, 2017). We find that utility models featuring individuals as patentees are licensed more quickly, which can be due to the fact that these inventors (mostly startups or non-affiliated researchers) depend on revenues from their technologies, causing a strong incentive to commercialize quickly. We do not observe these effects in the case of invention patents, but our findings suggest that inventions from universities are adopted later than inventions from firms. One reason for this effect might be that universities are more oriented towards basic research and thus dot not explicitly aim to invent marketable technologies. In addition, universities' technology transfer offices often lack capabilities to commercialize inventions (A. Chen, Patton, & Kenney, 2016; Markman et al., 2005).

Table 10: *Results for lognormal accelerated failure time models on time-to-adoption (patent-licensing variables only)*

	(5.1a) All patents	(5.1b) Utility models	(5.1c) Inventions	(5.2a) Utility models	(5.2b) Inventions	(5.3a) Utility Models	(5.3b) Inventions
dist	0.0075***	0.0054***	0.0095***				
	(0.0013)	(0.0018)	(0.0018)				
intra_pref				-0.0376***	-0.0839***		
				(0.0180)	(0.0194)		
intra_prov						-0.0701***	-0.1035***
						(0.0213)	(0.0209)
ipc	-0.0090**	-0.0187***	0.0017	-0.0189***	0.0022	-0.0186***	0.0017
	(0.0038)	(0.0060)	(0.0047)	(0.0060)	(0.0047)	(0.0060)	(0.0047)
claims	-0.0014	0.0022	-0.0040	0.0023	-0.0040	0.0022	-0.0042
	(0.0019)	(0.0028)	(0.0026)	(0.0028)	(0.0026)	(0.0028)	(0.0026)
fwd_cit	0.0194	0.0963***	-0.0029	0.0979***	-0.0025	0.0956***	-0.0020
	(0.0122)	(0.0312)	(0.0128)	(0.0312)	(0.0128)	(0.0312)	(0.0128)
indiv	-0.0387***	-0.0666***	0.0128	-0.0693***	0.0158	-0.0634***	0.0152
	(0.0148)	(0.0179)	(0.0260)	(0.0182)	(0.0262)	(0.0183)	(0.0261)
uni	0.0412**	-0.0199	0.0953***	-0.0224	0.0924***	-0.0159	0.0955***
	(0.0187)	(0.0378)	(0.0230)	(0.0382)	(0.0232)	(0.0379)	(0.0230)
excl	-0.0175	-0.0153	-0.0427	-0.0168	-0.0420	-0.0116	-0.0407
	(0.0284)	(0.0431)	(0.0374)	(0.0436)	(0.0375)	(0.0431)	(0.0373)
util	-0.6870***						
	(0.0150)						
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Green domain dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	7.1400***	6.4098***	7.1768***	6.4498***	7.2521***	6.4716***	7.2722***
	(0.0440)	(0.0606)	(0.0560)	(0.0617)	(0.0614)	(0.0626)	(0.0619)
Log(Scale)	-0.5730***	-0.5388***	-0.6584***	-0.5384***	-0.6568***	-0.5391***	-0.6579***
	(0.0100)	(0.0113)	(0.0194)	(0.0114)	(0.0194)	(0.0114)	(0.0195)
Observations	8954	5446	3508	5446	3508	5446	3508
Log-Likelihood	-68181.7***	-40096***	-27974***	-40098***	-27980***	-40094***	-27976***

Notes: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$,* $p < 0.1$. The AFT models do not assume the proportionality assumption; the hazard functions follow a lognormal distribution. Negative (positive) coefficients indicate an accelerating (decelerating) effect on the time before a patent is licensed. The natural exponent of a coefficient gives the acceleration factor (i.e. time ratio).

5.4.2 Supply-side and demand-side region-specific effects on time-to-adoption for inter-regional licensing

As the next step, we estimate models including regional variables added for either the licensor region or the licensee region (see Table 11). Regional variables for the licensor region reflect regional effects on the supply side, i.e. innovation development, which might accelerate (decelerate) the commercialization. Regional variables for the licensee region reflect regional effects influencing time-to-adoption from the demand side. For these models, we exclude intra-regional license agreements (*intra_pref* equals 0). We use shared frailty terms to capture unobserved heterogeneity on the regional level and, as an alternative, clustered standard errors for models 8a and 8b in Table A.4 in Appendix C. On the demand side, we do not find any significant regional factors that accelerate or decelerate time-to-adoption. There is also no difference between utility models and inventions in that regard, with geographic distance remaining an important factor in explaining the time-to-adoption of green technologies. On the supply side, however, regional factors matter. That is to say, we find positive effects of *green_lic_out*, pointing to the fact that time-to-adoption is slowed down the higher the number of previous licensors in the region is, contradicting what we expected in P2b. However, we find accelerating effects of non-green regional innovation capabilities (*inno*) for the time before an invention patent is licensed, indicating that, net of other effects, actors in innovative regions are faster to license out their green technologies. For utility models, on the other hand, we find that regional specialization in green technologies (*rpa*) is associated with licensors being able to license out faster, supporting P3b.

In summary, distinguishing between regional demand-side and supply-side effects for inter-regional green technology diffusion suggests that the former does not matter while the latter does. With green technological specializations and regional innovation capabilities affecting inter-regional diffusion only from the supply side, (regional) demand-side factors explaining early adoption might stem from user-related characteristics and localized institutions that we are unable to include in our analyses (see T. Hansen & Coenen, 2015).

Table 11: *Results for lognormal accelerated failure time models on time-to-adoption (inter-regional licensing)*

	(5.4a)	(5.4b)	(5.4c)	(5.5a)	(5.5b)	(5.5c)
	Demand side (licensee region)			Supply side (licensor region)		
	All patents	Utility models	Inventions	All patents	Utility Models	Inventions
green_lic_in	0.0229	0.0504	0.0155			
	(0.0400)	(0.0561)	(0.0508)			
green_lic_out				0.0736***	0.0809**	0.1015***
				(0.0233)	(0.0351)	(0.0292)
inno	-0.0014	-0.0025	-0.0023	-0.0095***	-0.0023	-0.0114***
	(0.0041)	(0.0058)	(0.0051)	(0.0036)	(0.0056)	(0.0042)
rpa	-0.0002	-0.0002	0.0005	-0.0021***	-0.0033***	-0.0006
	(0.0005)	(0.0008)	(0.0007)	(0.0005)	(0.0007)	(0.0007)
eco_reg	0.1215*	0.0870	0.0584	0.0925	0.0822	-0.0166
	(0.0727)	(0.0738)	(0.0551)	(0.0974)	(0.0783)	(0.0762)
pop	-0.0084	-0.0030	-0.0184	-0.0925	-0.0332	-0.0701
	(0.0830)	(0.0630)	(0.0486)	(0.0903)	(0.0655)	(0.0608)
pop_dens	-0.0620	-0.0587	-0.0269	0.0083	0.0011	0.0078
	(0.0560)	(0.0474)	(0.0377)	(0.0672)	(0.0519)	(0.0474)
dist	0.0081***	0.0056**	0.0075***	0.0077***	0.0093***	0.0062***
	(0.0017)	(0.0025)	(0.0022)	(0.0017)	(0.0025)	(0.0021)
util	-0.7077***			-0.7073***		
	(0.0230)			(0.0228)		
Patent-licensing controls	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
Green domain dummies	Yes	Yes	Yes	Yes	Yes	Yes
Frailty	Yes	Yes	Yes	Yes	Yes	Yes
Constant	7.5183***	6.8245***	7.4004***	8.4508***	6.9323***	8.0355***
	(1.1429)	(0.8896)	(0.6766)	(1.2411)	(0.9315)	(0.8373)
Log(Scale)	-0.6582***	-0.6243***	-0.7660***	-0.6560***	-0.6289***	-0.7591***
	(0.0120)	(0.0168)	(0.0174)	(0.0118)	(0.0166)	(0.0171)
Observations	3502	1813	1689	3600	1856	1744
Log-Likelihood	-26732***	-13244***	-13367***	-27496***	-13546***	-13820***

Notes: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$,* $p < 0.1$. The AFT models do not assume the proportionality assumption; the hazard functions follow a lognormal distribution. Negative (positive) coefficients indicate an accelerating (decelerating) effect on the time before a patent is licensed. The natural exponent of a coefficient gives the acceleration factor (i.e. time ratio). Patent-licensing controls (ipc, claims, fwd_cit, indiv, uni, excl) not reported. Models include shared frailty terms to account for heterogeneity at the regional level.

5.4.3 Region-specific effects on time-to-adoption for intra-regional licensing

For models 5.6a to 5.7c in Table 12, we only consider intra-regional licensing (*intra_pref* equals 1, see also models 5.8c and 5.8d in Table A.4 in Appendix C). In this scenario, regional effects arise both for the demand side and for the supply side. We find that regional innovation capabilities in non-green technologies (*inno*) accelerate intra-regional time-to-adoption across several model specifications. The higher the regional innovation capabilities, the faster environmental innovations diffuse within the region. Moreover, early adoption of local technologies is accelerated the more a region specializes in green technologies (*rpa*), supporting P3a and P3b. While the number of previous licensors and licensees in a region seems to decelerate time-to-adoption for invention patents, we find an accelerating effect of both previous licensors and licensees for utility models. These results suggest that the diffusion of low-tech environmental innovations (utility models) is facilitated, while high-tech innovations (invention patents) seem to diffuse more slowly within a region the higher the number of green technology actors in that region is. We thus find no uniform pattern for P2a and P2b for utility models and invention patents. It appears that the positive regional demonstration and learning effects that we assumed only exist for utility models. For invention patents, innovators may more frequently reach adopters outside their home region simply because the number of potential adopters of high-level technology is much more limited to a small group of sophisticated firms for which demonstration effects are less important.

Table 12: Results for lognormal accelerated failure time models on time-to-adoption, intra-regional licensing

	(5.6a) All patents	(5.6b) Utility models	(5.6c) Inventions	(5.7a) All patents	(5.7b) Utility Models	(5.7c) Inventions
green_lic_in	-0.0144	-0.0684**	0.0742**			
	(0.0236)	(0.0293)	(0.0365)			
green_lic_out				-0.0309	-0.0771***	0.0494*
				(0.0193)	(0.0242)	(0.0295)
inno	-0.0200***	-0.0140***	-0.0196***	-0.0195***	-0.0130***	-0.0194***
	(0.0035)	(0.0046)	(0.0047)	(0.0036)	(0.0047)	(0.0047)
rpa	-0.0019***	-0.0012**	-0.0021***	-0.0019***	-0.0011*	-0.0021***
	0.0005	(0.0006)	(0.0007)	(0.0005)	(0.0006)	(0.0007)
eco_reg	0.0026	0.0160	-0.0246	-0.0035	0.0091	-0.0219
	(0.0728)	(0.0638)	(0.0740)	(0.0729)	(0.0640)	(0.0739)
pop	0.1243	0.1580**	0.0293	0.1259	0.1591**	0.0317
	(0.0974)	(0.0635)	(0.0641)	(0.0974)	(0.0637)	(0.0640)
pop_dens	-0.0211	-0.0518	0.0449	-0.0181	-0.0505	0.0471
	(0.0725)	(0.0513)	(0.0506)	(0.0725)	(0.0515)	(0.0505)
util	-0.6341***			-0.6327***		
	(0.0187)			(0.0187)		
Patent-licensing controls	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
Green domain dummies	Yes	Yes	Yes	Yes	Yes	Yes
Frailty	Yes	Yes	Yes	Yes	Yes	Yes
Constant	5.5731***	4.4595***	6.7627***	5.5347***	4.4417***	6.7179***
	(1.3151)	(0.8667)	(0.9162)	(1.3138)	(0.8685)	(0.9140)
Log(Scale)	-0.6053***	-0.6003***	-0.7050***	-0.6056***	-0.6010***	-0.7045***
	(0.0097)	(0.0119)	(0.0170)	(0.0097)	(0.0118)	(0.0170)
Observations	5353	3590	1763	5353	3590	1763
Log-Likelihood	-40208***	-26161***	-13888***	-40206***	-26159***	-13889***

Notes: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$,* $p < 0.1$. The AFT models do not assume the proportionality assumption; the hazard functions follow a lognormal distribution. Negative (positive) coefficients indicate an accelerating (decelerating) effect on the time before a patent is licensed. The natural exponent of a coefficient gives the acceleration factor (i.e. time ratio). Patent-licensing controls (ipc, claims, fwd_cit, indiv, uni, excl) not reported. Models include shared frailty terms to account for heterogeneity at the regional level.

5.4.4 Limitations and robustness

Of course, the results presented in this article are subject to certain limitations, some of which deserve a brief discussion. Firstly, in many respects our results only hold for the early adoption of environmental innovations, and do not reflect the entire diffusion process. In fact, patents are only an indicator for a subset of environmental innovations as they are restricted to patentable technological innovations. Consequently, patent-based analyses of the diffusion process of environmental innovations are strongly production-oriented, whereas organizational innovations such as changes of production processes might not be captured. Furthermore, it is not entirely clear to what extent the results are biased toward the use of licensing as an indicator, as the licensing process itself is often highly regionalized (see section 5.3.1). Future studies should examine the time-to-adoption of green technologies with other data (e.g. surveys), although we explicitly emphasize the advantages of using licensing data for the study of innovation diffusion. Moreover, it is unclear to what degree China-specific factors such as patenting subsidies affect our results. Readers should also not confuse the adoption of a new technology by producers with the adoption by final customers.

An important caveat to consider when interpreting our results is the potential endogeneity of geographic distance, as licensees may actively choose to locate close to potential licensors. Given the lack of more detailed information on licensees, we are not able to create an instrumental variable to control for the endogeneity of distance. We are confident, however, that endogenous location choices remain unlikely, as licensees are not necessarily newly formed organizations. In fact, endogenous location choices are most likely for spin-offs from universities and research institutions (Buenstorf & Schacht, 2013). Accordingly, we estimated models with universities and research institutions excluded. The results are robust to this modification, limiting issues arising from potential endogeneity. Nevertheless, we cautiously interpret our results as associations and correlations rather than causal relationships. We conducted a number of further robustness checks using different variables, data subsets or estimation strategies, which we discuss in more detail in Appendix C. In short, our results are robust against most modifications, with geographic distance being significant in all estimations.

5.5 Summary and policy recommendations

In this article, we used a unique data set on licensing agreements for green technology patents to study innovation diffusion in China. In more detail, we employed survival models to study how geographic proximity between innovator and adopter as well as region-specific characteristics affect the time-to-adoption of environmental innovations. For inter-regional licensing agreements, we considered region-specific effects for both the innovator's region (supply side) and the adopter's region (demand side). In a separate set of models, we focused on intra-regional licensing.

The major empirical results can be summarized as follows: most notably, geographic proximity to the innovator is associated with an accelerated time-to-adoption of environmental innovations, strongly supporting P1. For the other propositions, results differ between utility models and invention patents as well as between inter-regional and intra-regional diffusion. The presence of other green technology users in the adopter's region does not matter for the speed of inter-regional licensing. For intra-regional licensing, it accelerates the licensing of utility models but slows down licensing of invention patents, providing mixed results for P2a. The presence of other green technology innovators in the innovator's region decelerates the time-to-adoption for inter-regional licensing. Concerning intra-regional licensing, the results for P2b are similar to those for P2a, namely an acceleration for utility models and a deceleration for invention patents. Apart from that, regional green specialization has a significant accelerating effect in the case of intra-regional licensing, but only for the innovator's region in the case of inter-regional licensing, which gives partial support for P3a and somewhat stronger support for P3b.

In a nutshell, the article provides empirical evidence of a strong distance-decay of the speed of technology adoption that is statistically linked to geographic proximity to the innovator. Technologies developed in regions with green specialization will be adopted more quickly, both in other regions and in the region itself. Although the article's aims were empirical, and statistical results do not necessarily imply causal relations, it seems rational to link these findings to the notion of trust-based and frequent contacts that facilitate the sharing of tacit and complex knowledge. The results call for a differentiated and actor-sensitive view on the role of proximity in the diffusion processes of environmental innovation. At least in the current stage of development, it seems important to stress inventor-adopter relations, as they have shown to be distance-sensitive despite the fact that technology licensing is a rather standardized and codified form of technology transfer: proximity-facilitated contacts between inventors and adopters are important for the speed of green technology diffusion.

The findings can be carefully translated into policy implications. The current debate on policy instruments that help to speed up green technology diffusion discusses the more traditional supply-side instruments such as R&D incentives and demand-side elements including purchase incentives, public procurement, taxes etc. (Costantini, Crespi, & Palma, 2017). According to this article's findings, this policy mix should be complemented with measures that target specifically the technology licensing stage of the green technology adoption and diffusion process. It seems promising, firstly, to encourage contacts and exchanges between green technology inventors and potential adopters within their regional settings, since these contacts have a greater chance of resulting in licensing. Further extending this argument, it seems important, secondly, not to decouple R&D-related policies from production and demand-related policies. Instead, these policies should be coordinated to deliver targeted green technology support that addresses invention and production. This should be done within specialized regions and within settings of proximate regions (Hansmeier & Losacker, 2021; Tödtling et al., 2021). It is hence advisable, thirdly, not to develop regional policies for the technology invention phase and for the production phase independently, but to align the policy instruments at least in those technology fields and industries where competencies overlap.

CHAPTER SIX

The Geography of Environmental Innovation: A Critical Review and Agenda for Future Research

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Abstract

Environmental innovations make an important contribution to solving ecological and climate crises. Although these crises are global phenomena, the regional dimension plays a crucial role, as regions both provide the conditions for the development of environmental innovations and promote widespread use and diffusion. Against this background, this article has two objectives. Firstly, we critically review the state of research on regional determinants of environmental innovation. Secondly, based on these results, we develop an agenda for further research in regional studies that will help to better understand the geography of environmental innovation and to come up with useful region-specific policy recommendations.

6.1 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. Environmental innovation is indeed an inherently geographic phenomenon, as the underlying innovation processes involve region-specific bundles of factors that determine the particularities of the innovations developed and adopted.

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. While much of this literature refers to the early innovation process, such as technology development (Barbieri, Perruchas, et al., 2020; D. Li, Heimeriks, & Alkemade, 2021; Montresor & Quatraro, 2020; Santoalha & Boschma, 2021), some deals with the production of environmental innovations and their markets, namely green industries and green regional development (Gibbs & O’Neill, 2017; Grillitsch & Hansen, 2019; Trippl et al., 2020). Moreover, researchers working in the field of sustainability transitions are investigating which spatial factors contribute to the diffusion and legitimacy of environmental innovations, enabling transformations of socio-technical systems beyond the regional level (Binz et al., 2020; Binz, Truffer, & Coenen, 2014; Rohe & Chlebna, 2021). In addition to this trend of geographers addressing the various facets of environmental innovation, researchers from the broader fields of innovation studies or environmental economics are increasingly focusing on spatial issues in their research as well (Antonioli et al., 2016; Cainelli et al., 2012; Horbach, 2014; Horbach & Rammer, 2018). Consequently, a large body of literature has emerged in recent years that, to put it concisely, addresses *the geography of environmental innovation*.

Research on the geography of environmental innovation has been unbalanced, however. Analyses of the regional conditions affecting the generation of environmental innovations tend to dominate, while the equally important aspects of scaling-up and diffusion as well as the role of basic regional characteristics that affect environmental innovations have so far been under-researched. Moreover, the state of research is fragmented across several disciplines, and geographical literature lacks a critical overview of the importance of regions in the development and diffusion of environmental innovations. At the same time, a research agenda at the intersection of regional studies and environmental innovation is still missing. 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, including both innovation emergence and diffusion. We thus seek to identify 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. The agenda is designed for researchers from core geographic fields such as human or economic geography, regional studies and regional science, but it will also be helpful for geographically interested researchers from environmental economics, innovation studies or sustainability transitions, among other fields.

The remainder of this article is structured as follows. In Section 6.2, we discuss the conceptual background and the characteristics of environmental innovation and how they are relevant from a regional perspective. Section 6.3 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 6.4, we provide suggestions for future research based on the review. In this context, we point to important regional factors that have been neglected so far and, on a more general level, we call for a demand-side turn in research on the geography of environmental innovation. Our concluding remarks are presented in Section 6.5.

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

An environmental innovation 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 & 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).

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 & Rennings, 2005b; Jaffe et al., 2005; Rennings, 2000).

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, the regulatory push/pull, is required to stimulate environmental innovations (Rennings, 2000). Environmental 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 & van der Linde, 1995; Rexhäuser & Rammer, 2014). Based on these theoretical approaches, numerous empirical studies have examined the determinants of environmental innovation (Hojnik & 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, market characteristics)
- Demand-side determinants (e.g. expected market demand, environmental awareness)
- Institutional and political determinants (e.g. environmental policies and regulations, innovation networks)

Apart from the institutional and political determinants, which 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 & 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 CO_2 emissions (Mealy & Teytelboym, 2020). Moreover, employment in green industries has a multiplying effect and can be linked to the creation of additional jobs in a region. 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 & Anderson, 2021). 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.

6.3 The geography of environmental innovation: regional determinants

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. In Section 6.4, we will outline under-researched issues in these three spheres and additionally discuss the need to extend the research focus towards the influence of basic regional characteristics. While there are already useful systematic literature reviews that deal with the determinants of environmental innovations (Barbieri et al., 2016; Hojnik & Ruzzier, 2016; Horbach, 2019), we limit our review to those studies that have an explicit implication for regional studies. As mentioned before, three different groups of factors have been examined in detail in the related 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.

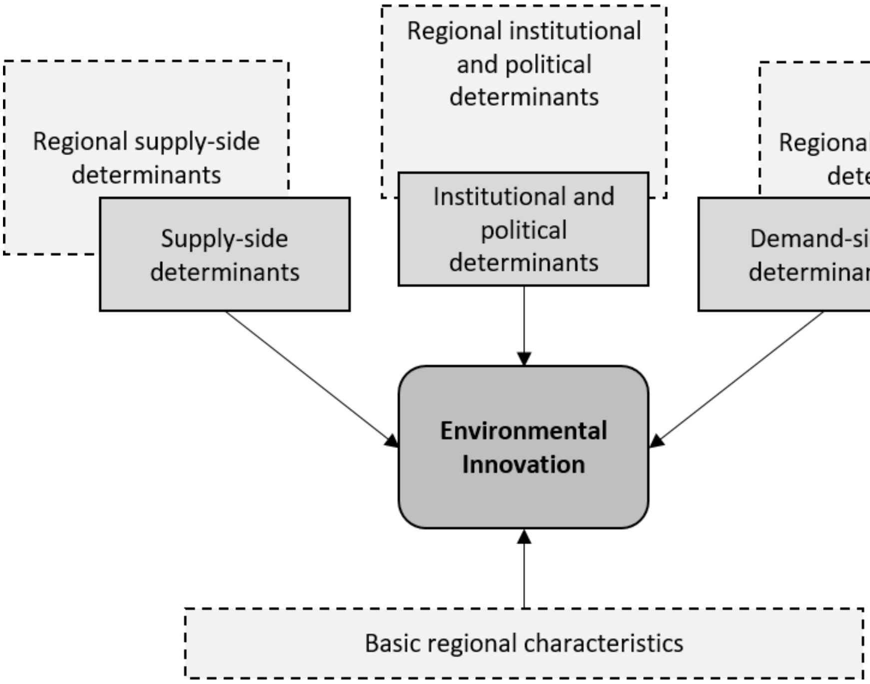

Figure 9: *Determinants of environmental innovation*
(own figure, based on Horbach, 2008, 2019; Rennings, 2000)

In Figure 9, we present the three groups of determinants usually discussed in the literature, adding the regional dimension to each of these factors. Figure 9, in that sense, visualizes the underlying conceptual framework of this article and the structure of Sections 6.3 and 6.4. Table 13 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.

Table 13: Regional determinants of environmental innovation

Regional supply-side determinants
• Green technologies are 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 • The diffusion of environmental innovations strongly depends on technology legitimization, which can differ profoundly between regions • Regional environmental awareness and green political orientation induce the development and diffusion of green technologies • Lead market regions can demonstrate the positive effects of an environmental innovation and pioneer its applicability. Other regions and nations anticipate the benefits and follow the lead market's example
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

6.3.1 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 & 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 has been demonstrating for more than two decades (Asheim, Grillitsch, & Trippl, 2016). However, given their higher complexity (Barbieri, Marzucchi, et al., 2020), 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 & Scandura, 2019) while they also require higher human capital inputs (Horbach, 2014). These empirical findings emphasize the importance of universities in 'green regional innovation systems' (Cooke, 2010), marking them as crucial actors in analyses of (the geography of) environmental innovations. Other supply-side regional determinants of green technology development include, inter alia, local knowledge stocks, agglomeration economies, and public research subsidies (Arranz, Arroyabe, & Arroyabe, 2019; Corradini, 2019; Corsatea, 2016; Giudici, Guerini, & Rossi-Lamastra, 2017). Moreover, green technologies often stem from teams of inventors who are able to creatively recombine existing knowledge (Orsatti, Quatraro, et al., 2020). They also generally require a higher degree of R&D cooperation and external knowledge in the developmental phase (Cainelli, De Marchi, & Grandinetti, 2015; De Marchi, 2012; Ghisetti et al., 2015; Horbach et al., 2013). In that regard, collaborative R&D processes will be particularly beneficial to environmental innovation emergence if partners are located in close geographic proximity (Ardito, Petruzzelli, Pascucci, & Peruffo, 2019; Cainelli et al., 2012; Chiarvesio, De Marchi, & Di Maria, 2015). These 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.

Additional insights can be gained from an evolutionary perspective on green technology development in regions. 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). Diversifying into green technologies will also 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 (Santoalha & 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. (2020) 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 technologies (Montresor & Quatraro, 2020).

Similar mechanisms also apply at the industry level. From an evolutionary perspective, regional preconditions will strongly affect the way diversification in green industries might take place. Based on these considerations, Grillitsch and Hansen (2019) introduce a typology for green industry development in different types of regions, distinguishing between peripheral regions and metropolitan regions as well as between regions already specialized in green industries and regions specialized in dirty industries. Peripheral regions, for instance, will need to focus their developmental strategies on path emergence and path upgrading processes, supporting the growth of new green industries. Regions that specialize in dirty industries, on the other hand, might focus on new technologies that clean the existing industry or they might focus on diversifying into green activities that build on existing competencies, following a related diversification rationale (Grillitsch & Hansen, 2019). While these conceptualizations help to uncover the importance of regional heterogeneity, single firms as well as broader system-level actors do play a crucial role in green regional path development (Sotarauta et al., 2021; Trippl et al., 2020). That is to say, pioneering firms might contribute to the formation of local green industries, affecting regional development through agentic processes of asset modification, as do other (non-local) actors such as national policymakers or NGOs (Holmen & Fosse, 2017; H. Martin & Coenen, 2014; Trippl et al., 2020). In that regard, green path development will, in many cases, not only depend on regional factors, but also on the interconnection of regional factors and (global) industry or technology dynamics (Nilsen & Njøs, 2021; Njøs, Sjøtun, Jakobsen, & Fløysand, 2020).

6.3.2 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 & 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 (Corsatea, 2016; Giudici et al., 2017; 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 & 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). Moreover, 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 & Mignon, 2017; Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007). As technology legitimization results particularly from place-specific factors such as localized institutions, legitimacy will differ between regions, leading to differences in diffusion rates across space (Heiberg, Binz, & Truffer, 2020; Rohe & Chlebna, 2021).

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 & Kemp, 2008; Porter & 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 & 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 & Gillingham, 2015; Wolske, Gillingham, & Schultz, 2020).

These diffusion mechanisms stemming from the demand for environmental innovations not only take effect between adopters in a given region, but also between different regions, following the notion of (regional) lead markets. Lead market regions demonstrate the positive effects of innovations and can drive their international diffusion (Beise & Rennings, 2005b; Quitzow et al., 2014). Other regions and nations anticipate the benefits of an innovation that the lead market has already implemented and follow its example. The result is a simple spatial pattern of innovation diffusion with one pioneering region and many laggards. The concept of lead markets has proven particularly useful explaining the diffusion of environmental innovations, as they depend strongly on regulations and local demand conditions (Horbach et al., 2014; Rennings, 2014; Walz & Köhler, 2014). Although lead markets are mostly studied at the national level, recent case studies also show that lead markets can emerge at the regional level, steering interregional as well as international environmental innovation diffusion (Cooke, 2011; Losacker & Liefner, 2020b).

6.3.3 Regional institutional and political determinants

It has long been recognized that regulations and policies are key to environmental innovation (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, D'Amato, & Mazzanti, 2015; Frey, 2012; Popp, 2010; Woerter, Stucki, Arvanitis, Rammer, & Peneder, 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 & Sato, 2017; Johnstone, Haščič, Poirier, Hemar, & Michel, 2012; Johnstone, Haščič, & Popp, 2010). 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 (Beise & Rennings, 2005b). 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 & Glachant, 2013; Herman & Xiang, 2019; Popp, 2006). In particular, policies on the national or supra-national 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, Deng, Song, Zhong, & Zhu, 2019; Corsatea, 2016; Losacker & Liefner, 2020b).

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 & 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 & Liefner, 2019; Nesterova, Quak, Streng, & Dijk, 2020). Green public procurement, however, also exhibits positive effects on future green technology development within a region (Orsatti, Perruchas, Consoli, & Quatraro, 2020).

6.4 Suggestions for future research

As outlined in Section 6.3, several traditional determinants of environmental innovation bear an explicit regional imprint. In this section, we propose avenues for further research on the regional dimension linked to the supply side, the demand side, and to institutional and political factors. We will argue that research on the geography of environmental innovation will need to focus on the use of technologies and on demand-side issues. In addition, we point to a set of further regional factors that have largely been ignored in the literature on environmental innovation. Table 14 presents research questions that we consider to be important.

6.4.1 Regional supply-side determinants: towards the interplay of green and digital technologies

Regarding the inputs for the development of environmental innovations, much research has already been conducted on supply-side factors (see Section 6.3.1), including the role of other (related) technologies and regional innovation capacities. Often overlooked, however, are enabling technologies, which do not necessarily have to be related to green technologies per se or lie in the same technological domain. In this context, digital technologies could play a major role for the development and application of environmental innovations, for example in the areas of energy or resource efficiency. Particularly at the regional level, the question arises as to the extent to which digital technologies can increase the capabilities to innovate in green domains. Digital technologies might also help to establish regional circular economies and to clean production processes. While some studies already explore this nexus to some extent (Montresor & Quatraro, 2020; Santoalha, Consoli, & Castellacci, 2021), more research in regional studies will be needed, especially against the background of the new funding period (2021-2027) of the EU regional policy that focuses on so-called ‘twin transitions’, that is, both green and digital transformations in regions.

6.4.2 Regional demand-side determinants: towards a demand-side turn

One of the most important differences between the *geography of innovation* and the *geography of environmental innovation*, 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 when they are widely diffused. 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. 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. This demand-side turn in geographical research on innovation 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 transportation sectors, and to provide feedback effects on the further development of green technologies. We will discuss a number of regional factors that matter in this regard in Section 6.4.4. 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 (Losacker, 2022).

6.4.3 Regional institutional and political determinants: towards regional regulations and multi-level policy effects

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. The question is: to what extent do regional environmental policies have the same positive effects on environmental innovation as policies at the national or international level? This also raises the need for research approaches employing multi-level designs that take into account both regional and national regulations and 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, Truffer, & Kallis, 2011), and the multi-level governance thereof.

6.4.4 The role of basic regional characteristics: towards a focus on demographics, infrastructures and industries

In addition to the spatial dimension of the traditional determinants of environmental innovation discussed so far (supply-side, demand-side, institutional and political factors), a number of further regional factors affect development and diffusion processes. These factors, however, have largely been neglected in the geography of environmental innovation literature.

Firstly, regional demographic and socio-economic factors are likely to affect how regions develop and use environmental innovation. While some studies have begun to explore the effects of regional environmental awareness or green attitudes on environmental innovation (see Section 3.2), there is much room for further research. In fact, the effects of environmental awareness and green attitudes are complemented by additional demographic factors such as age, education, employment and income. These (basic) individual factors have received much attention in the literature on green consumer behavior, but it has not yet been fully explained how they translate to the regional level. It will be necessary to examine the links between these regional characteristics and the capacity of regions to create environmental innovations. At the same time, the question arises as to how the demand for, and thus the use of, environmental innovations differs between regions characterized by different demographic and socio-economic structures, e.g. regions with rapidly aging populations versus regions with young populations.

Secondly, many green technologies, in particular 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, Alkemade, & Hekkert, 2012; Unruh, 2000). In that sense, the physical infrastructure in a region works like a built regime and leads to tangible lock-ins of unsustainable technologies. 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. These barriers directly translate into regional path-dependencies, making it more difficult for some regions to transition into more sustainable modes of production and consumption (R. Martin & Sunley, 2006; Truffer et al., 2015). 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). From a geographical perspective, however, we can observe several examples of new decentralized infrastructure systems that allow environmental innovations to be used at the local level without being dependent on incumbent firms or rigid structures at the national level. These examples include, for instance, community energy initiatives for renewable energy (Bauwens, Gotchev, & Holstenkamp, 2016; Roesler & Hassler, 2019). Given that many (rural) areas will witness a rise in their urbanization rates in the coming decades, particularly in the global south, it will be necessary to design environmentally friendly infrastructures and built environments, avoiding further lock-ins into unsustainable pathways. Against this background, we feel that the impact of local infrastructures receives insufficient attention in research on the geography of environmental innovation. At this point, it is once again necessary to focus on the demand side and the use of technologies. How should green technologies in the fields of transport or energy be deployed if the infrastructure in many regions is not designed adequately?

Thirdly, the regional industry structure poses significant opportunities and challenges for different types of regions. While the role of the industry mix is usually discussed in the literature on green path development, analyzing how regions can diversify into green industries (Grillitsch & Hansen, 2019), 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.

Table 14: Directions for future research on regional determinants of environmental innovation

Regional supply-side determinants: towards the interplay of green and digital technologies
• To what extent can digital technologies and skills increase the capabilities to innovate in green domains? How does this relationship translate to the regional level? • How can regions successfully accomplish a 'twin transition', i.e. green and digital transformations? • What types of digital technologies (artificial intelligence, digital twins, internet of things, etc.) are useful for innovating in what types of green domains (climate change mitigation, waste management, environmental monitoring, etc.)? What roles do regions and geography play in this regards?
Regional demand-side determinants: towards a demand side turn
• What are the regional determinants that contribute to regions' success in using environmental innovation? Which regions will be in the spotlight in this regard – particularly when disregarding the highly innovative regions that usually receive much attention in the geography of innovation literature? • What roles do regions that increasingly use green technologies but are not directly involved in R&D activities (e.g. rural regions) have in the spatial organization of innovation processes? How important are feedback effects and DUI-modes of learning stemming from those regions for innovation and diffusion processes? • From a researcher's perspective, what kind of methodological approaches can fit or will need to be developed for studying the use of green technologies in regions as well as the spatiality of eco-innovation processes?
Regional institutional and political determinants: towards regional regulations and multi-level policy effects
• Can regional environmental policies have the same positive effects on environmental innovation as policies at the national or international level? • How do regional and national-level environmental policies interact in a multi-level governance system? How can regional policies improve the effects of higher-level policies? • How do place-based innovation policies (e.g. RIS3) interact with national and particularly regional environmental policies? What role can (place-based) mission-oriented innovation policies play in this context?
Basic regional characteristics: towards a focus on demographics, infrastructures and industries
• What demographic and socio-economic factors are important for the development and use of environmental innovation on the regional level? How do these factors relate to regional environmental awareness? • What is the role of (physical) infrastructure in regional environmental innovation and how do new and old infrastructures align with the use of green technologies? • How does the regional industry structure determine the development and particularly the use of environmental innovation? Which factors are important for the diffusion of green technologies in regions specialized in industries that are difficult to transform (e.g. agriculture, mining, manufacturing)?

Both researchers and policymakers need to understand that not every region can be an innovation cluster, for example for wind energy technologies - many regions will need to continue to produce steel needed for wind turbines, and it is important to understand how to make the production processes in these regions more sustainable. Similar arguments hold true for rural and agricultural regions. Rural regions will not contribute directly to inventing green technologies when compared to highly innovative regions, but it will be those rural regions that have great potentials to use greener technologies. We therefore, again, call for a demand-side turn in research on the geography of environmental innovations, helping to understand how regions can become more sustainable without completely substituting traditionally dirty industries with green ones, but rather greening the existing industries.

6.5 Conclusion

In this article, we set two research objectives. The first involved a critical literature review of the regional determinants of environmental innovations. For this purpose, we have analyzed research findings from the pertinent literature on supply-side factors, demand-side factors, and institutional or political factors, which take effect on the regional level or have explicit spatial implications. We conclude that regional determinants on the supply side play an important role for green technology development due to the positive effects of, for instance, regional R&D collaborations and regional university-industry collaborations in green domains. In addition, regional technological relatedness favors the development of environmental innovations. On the demand side, we find that regional environmental awareness and regional demonstration effects are pivotal to the emergence and diffusion of environmental innovations. Finally, (regional) environmental regulations induce both the development and the diffusion of green technologies. However, environmental policy effects have mostly been studied on the national level so far with limited evidence for the regional level. The findings of our literature review were used to address the second research objective in this article: developing an agenda for future research in regional studies on the geography of environmental innovations. We suggest that future research on supply-side determinants should pay increased attention to the interplay of green and digital technologies in regions. Moreover, we point towards the need to study regional environmental policy effects in greater detail, also looking at multi-level policy effects and combined environment-innovation policies. In addition to the set of regional factors that have been studied so far and fit into the traditional groups of determinants, we call for more research on other regional determinants. These include demographic and socio-economic factors on the regional level, regional infrastructures, and the regional industry structure. Most importantly, however, we call for a demand-side turn in research on the geography of environmental innovation. We claim that it is of utmost importance to understand how green technologies diffuse across space, given that their positive environmental effects only unfold when they are widely used. We should therefore shift the research focus from highly innovative regions that develop green technologies to those regions that are usually ignored in the geography of innovation literature, namely less innovative regions that could make great use of environmental innovations.

Last but not least, there are two issues that we need to mention in this article. Firstly, while many of our reflections have focused on geography in terms of regional factors, we would like to emphasize the value of a global and multi-scalar perspective, as global processes, both in innovation development and in market formations, are essential for many environmental innovations (Binz et al., 2014). The extent to which regional or global facets are important, however, depends very much on the technology or innovation being studied (Binz & Truffer, 2017; Rohe, 2020). Secondly, in the past decade, much has been written about the importance of regions for the transition of socio-technical systems (T. Hansen & Coenen, 2015; Truffer & Coenen, 2012; Truffer et al., 2015). While these authors describe particularly long-term and complex *transformation processes* and regional transition paths towards sustainability, our article has focused on the regional factors shaping the *innovation process* of green technologies that eventually enable deeper system changes. We therefore consider our article complementary to the previously mentioned contributions from the field of sustainability transitions.

CHAPTER SEVEN

Conclusion

7.1 Summary and main findings

In this dissertation, broadly speaking, I have studied the diffusion of environmental innovations in China. I have focused on three research objectives, the results of which are briefly summarized and discussed in this section. While all results have been discussed in greater detail in the respective chapters, this section will be limited to some of the main findings.

In research objective one, I aimed to develop a regionalized framework for the analysis of the spatial diffusion of environmental innovations. I pursued this goal in chapter two in particular, where we developed and presented the concept of regional lead markets for environmental innovation. The notion of regional lead markets is based on the original lead market concept developed by Beise (2004) as well as Beise and Rennings (2005b), rethought from a geographical perspective. The literature on the geography of innovation and sustainability transitions particularly contributed to adapting the concept to fit regional cases (e.g. T. Hansen & Coenen, 2015). In a nutshell, regional lead markets can be defined as sub-national regions with large markets that adopt a subsequently successful innovation at an early stage and gain a competitive advantage in the respective industry. They can drive national and international diffusion processes as well as global standardization. Regional lead markets will emerge in specific empirical contexts where the national lead market framework is less applicable, as lead market factors are constituted on the regional level. The regional lead market potential is particularly driven by regional technological advantages, regional demand and regional regulations as well as the interplay of these factors. Other lead market factors such as price and cost advantages, export advantages and transfer advantages might play a more important role on the national level. The framework has proven useful in explaining the lead market potential for environmentally benign waste management innovations in Shanghai.

In other chapters of this dissertation, especially in chapter four, it became evident how closely interrelated local demand and supply of environmental innovations are within a given region, supporting our conceptualizations. A regional lead market can also benefit from accelerated intra-regional innovation diffusion, which can further amplify the lead market potential, as illustrated in chapter five.

With regard to research objective two, I made use of the regional lead market framework to analyze the patterns and determinants of spatio-temporal environmental innovation diffusion processes in China. The research objective was mainly addressed via quantitative methods, using data for green technology patent licensing agreements as an indicator for innovation diffusion. In chapter three, evidence is provided that the majority of patent licensing agreements for green technologies are concluded within a prefectural region, meaning that the licensor and licensee are often geographically co-located. In chapter four, I also show for the case of inter-regional licensing that geographic proximity between licensor and potential licensee increases the likelihood of entering into a licensing agreement. The results obtained in this chapter also suggest that regional lead market structures strongly influence the diffusion of green technologies in China, as only very few regions are responsible for most diffusion processes, i.e. licensing activities. In chapter five, together with my co-authors, we focused not only on spatial patterns, but more strongly on the speed of innovation diffusion. We show that the time-to-adoption of environmental innovations is significantly accelerated when innovator (licensor) and adopter (licensee) are in close geographic proximity to each other. Geographical proximity thus not only increases the likelihood of innovation diffusion processes, but also their speed. Moreover, we find that intra-regional innovation diffusion is accelerated if the region is specialized in green technologies. For the case of inter-regional licensing, however, we find an accelerating effect only if the innovator's region is specialized in green technologies, while there is no such effect for the adopter's region.

Against the background of my own empirical results and the extensive engagement with the relevant literature, the final research objective in this dissertation was to critically appraise the role of regional factors for environmental innovation. We therefore conducted an integrative literature review on the regional determinants for the development and diffusion of environmental innovation. We applied a regional perspective to the standard determinants, including supply-side factors, demand-side factors as well as institutional and political factors. We found that regional factors on the supply side will especially contribute to the development of green technologies.

Local knowledge inputs, for instance through regional R&D networks or local universities, are particularly important for environmental innovations due to their higher complexity. In addition, related diversification and specialization processes will shape green regional paths. On the demand side, regional environmental awareness as well as demonstration effects can foster the diffusion of green technologies within a region, while inter-regional diffusion processes are likely to be orchestrated by lead market regions. Institutional and political factors such as environmental regulations are, of course, important on the national level, but they also take effect on the regional level. In addition, place-based innovation policies can contribute to the development and adoption of green technologies in regions. For a future agenda on regional determinants, we propose focusing on the interplay of digital and green technologies in regions and on the role of regional infrastructures, among other issues. We also call for a 'demand-side turn' in research on the geography of environmental innovation, as it is not sufficient to understand where green technologies are invented. It is much more important to understand where green technologies are used and how to foster diffusion processes.

7.2 Research limitations

The results of this dissertation are subject to a number of limitations. Most of these limitations stem from the data and methods employed and relate in particular to chapters three to five. Although there are significant merits to using licensing data as an indicator for innovation diffusion (see sections 1.4 and 4.3.2), a number of drawbacks remain. Unfortunately, the data used does not provide any information about the legal relationships between firms, meaning that I was not able to monitor subsidiary companies, for example. Against this background, a number of other factors can be identified that influence the diffusion of innovations, none of which, however, were available for the empirical analyses. These factors relate, among other things, to innovator and adopter characteristics such as age, size, R&D intensity and environmental awareness. It also remains uncertain as to which license agreements are published by the Chinese patent office in the first place, and whether there is a selection bias involved. In addition to the probable filtering process that only commercializable patents are licensed, strategic licensing cannot be entirely ruled out (Motohashi, 2008; Ruckman & McCarthy, 2017). Moreover, licensing might be a substitute strategy for patent co-applications (Hagedoorn, 2003), while the licensing process itself, apart from being an indicator of innovation diffusion, is highly localized, making it difficult to reduce reliability biases (Mowery & Ziedonis, 2015; Seo & Sonn, 2019a).

Some other limitations also remain. For instance, I did not compare green and non-green technologies. While some of my results certainly depend a lot on the peculiarities of green technologies, basic patterns are probably very similar for non-green technologies. The same applies to differences between distinct green technology domains. Furthermore, it continues to be questionable as to what extent some of the results are specific to the Chinese context, as there is unfortunately no licensing data available for other nations or for international licensing agreements.

Although I use the term innovation diffusion throughout the dissertation, I do not describe the entire diffusion process in Rogers' sense (Rogers, 1962). I focus instead on the early diffusion phase. This should be kept in mind when interpreting my results.

One of the key findings of this dissertation is that licensing, and hence diffusion, is firstly more likely and secondly faster as a result of geographic proximity. However, the channels through which innovation diffusion is driven are not yet clear. On the one hand, it might be reasonable to seek licensing partners exclusively within the region in order to reduce information asymmetries and to better assess opportunistic behavior; on the other hand, it is also likely that licensing agreements will be concluded more frequently with existing local partners (Seo & Sonn, 2019a). Against this background, other forms of proximity are certainly also important for the diffusion process (Boschma, 2005), with social proximity and trust (i.e. guanxi, 关系) playing a crucial role in Chinese innovation processes (Fu, Schiller, & Revilla Diez, 2012; Losacker & Liefner, 2020a).

7.3 Theoretical contributions

This dissertation contributes to the understanding of spatial diffusion processes of environmental innovations, helping to advance conceptual frameworks at the intersection of various social science disciplines such as economic geography, innovation studies and transition studies. The dissertation thus responds to recent calls for more theoretical engagement with the geography of sustainability transitions (Binz et al., 2020). It also connects two research communities that, despite shared interests, hardly interact: eco-innovation scholars and sustainability transitions scholars (see Hansmeier, 2021). The dissertation builds on insights from both fields, bridging concepts and unveiling avenues for further research (see 7.5). It contributes to the knowledge on the geography of environmental innovation and sustainability transitions, broadly defined. Moreover, combining supply-side (innovation development) and demand-side (innovation adoption) perspectives on green technologies has shown that both play a role for understanding how diffusion processes are organized over geographical space. This finding will be particularly important for theoretical advancements in the eco-innovation community, which usually neglects the demand side and overestimates the supply side, while it will provide useful lessons for the sustainability transitions community, which, in contrast, overestimates the demand side and trivializes the supply side.

From a theory-building perspective, the greatest contribution of this dissertation is the introduction of the regional lead market framework, which offers useful lines of reasoning for the study of innovation diffusion. While the RLM framework is not to be understood as a holistic theoretical model, it does provide important building blocks for future theories. In that regard, it adds to the list of recent conceptual advancements that help to make sense of the geography of environmental innovation (Binz & Truffer, 2017; Ghisetti et al., 2015; Lema et al., 2021).

The empirical research in this dissertation has revealed that geographic proximity as well as several regional characteristics are crucial for the early diffusion of environmental innovations, thus stressing the importance of geography for the development of protected niches. In that sense, it adds quantitative evidence to the hypotheses on local sources of market formations (Dewald & Truffer, 2011, 2012).

Finally, the empirical findings in this dissertation provide a new understanding of the importance of geography for the speed of innovation diffusion in green technology domains. These findings will have significant implications for analyzing and understanding the next phase of ongoing sustainability transitions, i.e. the acceleration phase in which upscaling as well as faster time-to-markets will play a fundamental role (Markard, 2018; Markard et al., 2020).

7.4 Policy implications

Prior to presenting recommendations for policy action that build on the research that I have conducted in this dissertation, I would like once again to draw attention to the complex nature of sustainability transition processes. The complexity, manifested among other things by the interrelation of different sectors and spatial units, calls for equally complex policy measures that interlock in a well-coordinated policy mix

(Kivimaa & Kern, 2016; Rogge & Reichardt, 2016). The conclusions I derive in this section should therefore be interpreted only in light of such a policy mix.

That being said, this dissertation yields a number of rather general as well as some more specific recommendations for environmental and innovation policy. Broadly speaking, we have known for many years, as outlined particularly by Rennings' regulatory push/pull, that environmental policies and regulations are necessary to facilitate the diffusion of environmental innovations (Rennings, 2000). The famous Porter-hypothesis, arguing that environmental policies will lead to enhanced innovativeness in firms, which, as a consequence, might increase productivity and competitiveness, supports this line of reasoning (Porter & van der Linde, 1995). These observations imply that in political discourses, environmental and innovation policy - including economic policy and industrial policy in a broader sense - must not be considered in isolation, but there should rather be at least some kind of nexus, i.e. an environment-oriented innovation policy or an innovation-oriented environmental policy. In this regard, van den Bergh et al. (2011, pp. 6–7) emphasize: '*Environmental policy and innovation policy [...] in principle serve different (even though sometimes slightly overlapping) functions and should thus be seen as mainly complementary. From a theoretical economic viewpoint, the first is aimed at tackling negative environmental externalities, and the second at positive knowledge externalities. [...] However, having only one of these policies – environmental and innovation – in place is likely to have undesirable consequences*.' Some of these considerations can already be found in current policymaking (e.g. Walz et al., 2019), mainly revolving around the notions of mission-oriented innovation policies (Janssen, Torrens, Wesseling, & Wanzenböck, 2021; Mazzucato, 2018) and transformative innovation policies (Fagerberg, 2018; Schot & Steinmueller, 2018). These recent discussions in the innovation policy literature agree on the fact that the demand side and the role of the state are of significant importance in bringing about transformative change in the wake of environmental crises and grand societal challenges. In other words, we are facing a 'resurrection of the demand side' in current innovation policymaking (Edler & Georghiou, 2007). The demand side of innovation policy includes, in particular, the introduction of regulations and demand-enhancing legislation for environmental innovations (CO_2 taxes, feed-in tariffs, etc.) as well as public procurement favoring sustainable goods and services (Boon & Edler, 2018). The concept of regional lead markets introduced in this dissertation connects directly to this demand orientation in sustainable innovation policy. The lead market framework is by definition demand-focused (Beise, 2004), explaining how pioneering regions and countries can benefit from early market formation processes that eventually lead to competitive advantages in an industry. While the insights from lead market research are not new, and fundamentally support the demand focus in innovation policy, this dissertation brings an explicitly geographic perspective to the policy table. That is to say, innovation policy might be very effective when employing demand-side measures that are sensitive to space and regional specificities. In fact, most scholarly debates as well as current policymaking ignore place-based innovation policies that address the demand side. While regional innovation policies for the supply side such as the smart specialization framework do consider place specificities (Kroll, 2015; Tödtling & Trippl, 2005), demand-side policies put less emphasis on regional heterogeneity and sensitivity for space (Wintjes, 2012). The results of this dissertation, however, inform about the importance of region-specific demand conditions for (environmental) innovations, suggesting that policymakers should pay more attention to place-based innovation policies that target the demand side.

In addition, the results show how closely regional demand and supply of green technologies are related, making the case for a combination of demand and supply-side eco-innovation policies in meso-level governance (see also Hansmeier & Losacker, 2021). This recommendation builds on the reasoning by Tödtling et al. (2021) who elaborate on place-based policies for regional sustainability transitions that differentiate between production (supply) and application (demand) of green technologies. The results of this dissertation lead to an extension of these suggestions, pointing towards the win-win situation for the local economy and the environment when combining demand and supply-side policies. While this might foster the lead market potential for specific types of environmental innovations in some regions, these policy recommendations should not be interpreted as best-case scenarios, with effective policy implementation instead depending on various other factors including the local context and technology or industry dynamics.

In addition to these general recommendations, the results of this dissertation point towards more specific insights for policymakers. That is to say, the results show that geographic proximity and regional specializations are accelerating factors for the diffusion of green technologies. Policymakers should therefore aim to facilitate exchange between innovators and potential adopters within a region. At the same time, additional efforts will be needed to support the inter-regional diffusion of local technologies given lower diffusion rates and slower times-to-adoption. Innovation policy should therefore also consider the demand for green technologies in other regions or countries, for instance via aligning local innovation policies with environmental regulations in these (adjacent) markets. This strategy might prove useful to enhance a region's export and knowledge transfer advantages, also increasing its lead market potential.

7.5 Further research

The results of this dissertation leave some interesting questions unanswered, while at the same time opening up new avenues for research. Given the research agenda we have already set for the regional determinants of environmental innovation in chapter six, the recommendations in this section will be limited to immediate research opportunities arising from the results of this dissertation.

First and foremost, there is a great demand for further research on the concept of regional lead markets. The concept will need to be applied in further empirical studies in order to prove its value. These studies should cover both different types of regions and, in particular, different technological domains. In addition to case studies of successful single regions, multi-case study designs will provide new insights, as will large-scale quantitative studies. Assuming that both the development of environmental innovations and market formation are organized differently in global innovation systems depending on the innovation mode and the valuation mode of a given technology, the concept of regional lead markets might only be applicable for selected innovations (Binz & Truffer, 2017). Against this background, there is a pressing need for further research aimed at integrating the concept of regional lead markets with the notion of multi-scalar global innovation systems.

The literature on lead markets has so far been very sophisticated in its theoretical analysis and empirical investigation of critical success factors (Quitzow et al., 2014; Walz & Köhler, 2014). This has largely been achieved by analyzing one (or a few) leading regions or countries and their lead market potential. What remains unclear, however, is how regions or countries can sustain their competitive lead market advantage. Given prominent historical examples such as the lost lead market potential of PV in Germany, more research will be needed on which factors contribute to a lasting lead market position. In addition, it is very important for the global diffusion of environmental innovations to better understand the economic, technological, and spatial dynamics of different lag markets. How do lag markets anticipate the benefits of lead market innovations? How do lag markets participate in global value chains and innovation systems? How do various lag markets differ from one another, and are there other hierarchical structures, such as second-order lead markets, along the lines of the traditional diffusion literature?

The literature on (the geography of) environmental innovation has collected important insights on how green technologies emerge and how they diffuse, mainly referring to region-specific factors such as environmental regulations, technological capabilities or demand preferences. Inter-regional dynamics, however, are still underexplored. While evidence is strong that, for instance, local regulations foster the development of environmental innovations, the extent to which stringent regulations in other regions or foreign countries might also lead to increased green R&D is still unclear. Similar questions arise in the context of innovation adoption and diffusion: If local regulations will support the diffusion of environmental innovations, where do these innovations actually come from – domestic or foreign innovators? Empirical research on such inter-regional dependencies and dynamics will provide crucial insights, helping policymakers to adapt eco-innovation policies and green regional development strategies.

On a more general level, there is a strong need to explore appropriate indicators, data and methodologies for innovation research, as is the case for many other fields in the social sciences. Contemporary research on innovation diffusion is at an underdeveloped stage particularly due to a lack of data and indicators (Nelson, 2009). While large-scale standardized surveys such as the Community Innovation Survey have already resolved many questions about the emergence of (environmental) innovations (Horbach, 2008, 2016), such surveys might increasingly focus on the diffusion of innovations in the future. I encourage a greater effort to explore and evaluate new data sources, including patent licensing data. Moreover, where possible, innovation diffusion researchers might make their data freely available to others.

In general, I call for a more intensive dialogue between geography-motivated researchers in the fields of environmental innovation or environmental economics and researchers from the field of sustainability transitions. Both communities draw heavily on the theories and approaches from economic geography and, despite different foci, share a common interest in the spatial facets of environmental innovation (Hansmeier, 2021). I am confident that the exchange will contribute to further knowledge development and that the two fields can learn a lot from each other - for example regarding the advancement of research designs or empirical methods.

I feel optimistic that researchers in economic geography, alongside environmental economists or innovation and transition scholars, among others, will address the above-mentioned research gaps in the future, with an overall increase in research on more sustainable economies and societies. However, if research in economic geography is to seriously contribute to solving global environmental issues and the climate crisis, a more holistic view of economic processes across geographical space will be indispensable. It will not be sufficient to examine the production and supply side of economic processes exclusively. It will also be necessary to consider the application and demand side. In other words, as David Gibbs already advised some 15 years ago: '*Greater attention to the processes of consumption and a shift from economic geography's continued preoccupation with production are required to develop an environmental economic geography*' (Gibbs, 2006, p. 209).

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Appendices

Appendix A

This appendix serves to explicate the empirical approach and methods applied in this study. As mentioned in section 2.5.2, we combine three data types to analyze Shanghai's lead market potential for waste management technologies: (1) expert interviews and on-site visits, (2) extensive desk research and (3) quantitative patent analyses. We visualize the empirical strategy as a flow chart in Figure A.3.

Expert interview data: We conducted twelve semi-structured interviews with a wide range of experts. First, we interviewed representatives of two German waste incineration plants including on-site visits. These interviews mainly served to make sense of the global technological developments and to understand the technological innovation system. We extended this analytical base by interviewing an initial scientific expert on Chinese waste management. All remaining interviews were conducted during a research trip to Shanghai and involved four further scientific experts, two representatives of the Shanghai plant, one municipal government official as well as representatives of two other eco-innovating firms in Shanghai. Most interviews were conducted in Chinese with English or German translators, while some interviews were directly conducted in English or German. We were not able to record the audio for most interviews for reasons of discreetness. Instead, we made use of written records as well as technical sketches and photographs from the on-site visits. We analyzed our written records and postscripts following a qualitative content analysis approach. The three interviews with on-site visits in Germany and Shanghai lasted approximately four hours each while the remaining interviews lasted one hour on average. Our approach for selecting all relevant stakeholders for expert interviews followed a strategy of theoretical saturation. Once the interviews did no longer yielded new insights, we ended data collection. We further ensured that we interviewed all relevant stakeholders by choosing experts from different backgrounds. In particular, we talked to the most relevant actors in three areas: the plant's senior manager, the government official responsible for municipal waste management and the leading scientific advisor for the regulatory system.

Document data: Documents were analyzed in order to study both the empirical case as well as the broader technology and industry. We collected a wide range of documents which can be classified into five broader groups: newspaper articles, technical reports, company information, scientific studies and government documents. Our research assistants as well as our colleagues from China were instructed to search for all related documents in Chinese, while we searched for documents in English and German. In the first step, we collected newspaper articles as well as government documents dealing with waste management in Shanghai and China. Secondly, technical reports on waste incineration and on the best available technologies were collected and analyzed in order to understand innovative developments in the industry. Thirdly, we relied on newspaper articles, government documents and company information to examine the regulatory measures in Shanghai for waste management and its interrelation with local incineration plants. Finally, we updated our document collection and extended it by adding scientific studies. Government documents and newspaper articles were particularly important for assessing the regulatory and demand advantage, while technical reports, company information and scientific studies were important in order to understand the technological advantage. After initially scanning all documents, we filtered those that were found to be relevant for conceptualizing the lead market framework. The document data were also used for triangulation purposes, helping to evaluate the interview and patent data.

Patent data: This section not only provides information on the patent analysis conducted in this study, but also briefly introduces the GreenTechDB as an important data source for future research. Measuring environmental innovation and green technologies is crucial for scholars, policymakers, managers and further stakeholders. However, indicators are difficult to establish and efforts in data collection are needed (Arundel & Kemp, 2009; Kemp et al., 2019). In order to reveal the regional concentration of innovation activities, which indicate the technological advantage of regional lead markets, we use novel data retrieved from GreenTechDB (Perruchas et al., 2020, www.greentechdatabase.com). The database lists patent families from 1970 to 2010 extracted from PATSTAT (a patent family is a collection of different patents for similar technical content sharing a priority date). The database utilizes the ENV-TECH classification system for identifying environment-related technology patents, which are grouped into 8 domains, 36 subgroups and 95 technologies (Haščič & Migotto, 2015; OECD, 2016). Then, these patent families are geo-localized at the city level by employing inventors' addresses using different referencing methods such as

GeoNames and Google Maps API. Put together, the GreenTechDB constitutes a sophisticated data source on environment-related patents with high levels of disaggregation for both technology classifications and spatial units, allowing for manifold analyses on spatial and temporal dynamics of green technologies. Analyzing the spatial distribution of patents has a long tradition in economic geography and related fields with early contributions on Chinese regions (Yifei Sun, 2000). For environment-related patents, however, empirical studies are scarce, especially when it comes to China. Exceptions include, for instance, Yamei Sun et al. (2008), who map province-level differences considering an aggregate of green technologies focusing on patent ownership. Yu (2017) analyzes province-level differences for renewable energy generation technologies employing indicators such as total patent applications and the revealed technological advantage. Recently, Barbieri et al. (2020) found that green technology patents are not only more complex than non-green technologies, but also have a larger impact on future inventions. Using the GreenTechDB, we can improve this knowledge on environment-related patents in China, as our data source is based on patent families. We thus consider applications from more than 170 patent offices while previous studies focused on domestic applications only, hence neglecting patents that are invented in China but filed elsewhere. Patent families, therefore, are an indicator for patent quality and proxy market demand in countries other than China. Additionally, GreenTechDB follows a more reasonable and reproducible method to identify environment-related patents (ENV-TECH) and allows the localizing of invention activities down to the city level, which outperforms previous data sources. Table A.2 provides abbreviations and descriptions of the ENV-TECH classification system. The full classification including the respective IPC codes can be found in Haščič and Migotto (2015). Figure A.1 illustrates the uneven geography of environment-related patents in China, with Shanghai, Beijing and Guangdong leading in total patent family counts. In addition, Figure A.1 provides insight into which technologies show high patenting activities. For instance, enabling technologies in buildings (7_4) and technologies for renewable energy generation (4_1) register many more applications from Chinese inventors than environmental monitoring technologies (1_5). This helps to unfold the uneven geography of environmental innovation in China and also serves to show the potential of GreenTechDB for future analyses. Turning now to the actual analysis of this study and adding to the reported results in section 2.5.4: Figure A.2 is a standardized version of Figure 4. It maps the patent family count for waste-related technologies relative to 100,000 inhabitants based on data from the 2010 Chinese

Census. It reveals similar results to Figure 4: technological advantages in Beijing, Shenzhen and Shanghai. We also calculated the Relative Patent Activity (RPA) in section 2.5.4, following other lead market studies (Horbach et al., 2014; Köhler et al., 2014; Walz & Köhler, 2014). It measures technological specialization and is normalized between -100 and 100 with positive values indicating a high specialization. The RPA is based on the number of patents p in technology j and region i, and is given by:

$$RPA_{ij} = 100 \times \tanh \ln \left[\frac{p_{ij} / \sum_i p_{ij}}{\sum_j p_{ij} / \sum_{ij} p_{ij}} \right] \tag{8}$$

However, the RPA in section 2.5.4 could not be calculated using GreenTechDB, as this dataset lists inventor locations for green technologies only, while calculating the RPA requires regional patent data for the sum of all technological fields. Therefore, we made use of patent data from Incopat, a commercial Chinese patent database (see www.incopat.com). We retrieved regional patent data based on applicant locations, following the same ENV-TECH codes and time frames as mentioned before. Shanghai reveals a high level of specialization in waste-related technologies, scoring a RPA of 34.6 (see also section 2.5.4).

Analysis and triangulation: Based on these three data streams, we analyzed Shanghai's lead market potential for waste management. That is to say, we identified the three lead market factors that were found to be relevant on the regional level: regulatory advantage, demand advantage and technological advantage. Relying on different data sources has proven to be important in assessing different factors. For instance, the patent data was crucial for determining and understanding the technological advantage. For the regulatory advantage, we mostly relied on document data (particularly government documents and newspaper articles), while interviews with scientific advisors as well as government officials also helped to uncover the regulatory advantage. The demand advantage was analyzed based on interview and document data, with governmental reports and scientific studies being particularly important. The remaining lead market factors (price, transfer, export) were found to be less relevant on the regional scale according to the material we analyzed. Using three data types ensured methodological triangulation. In more detail (see Figure A.3), we included two main steps for triangulation. Firstly, we cross-validated information from our first interviews with document data. A second step for triangulation was included after analyzing all final data types separately.

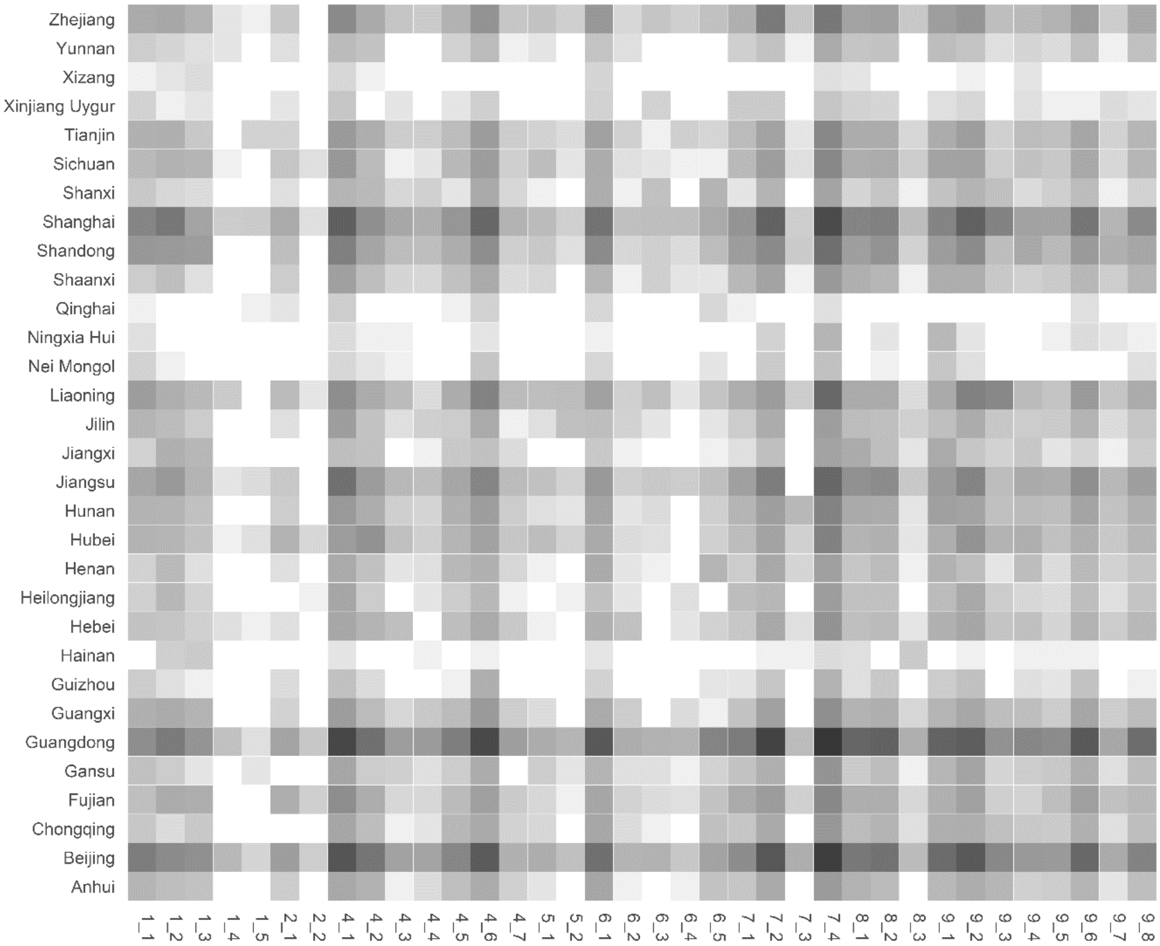


Figure A.1: Heatmap of green technology patents in China, patent families from 1970 to 2010, province-level
(data: GreenTechDB; Perruchas et al., 2020)

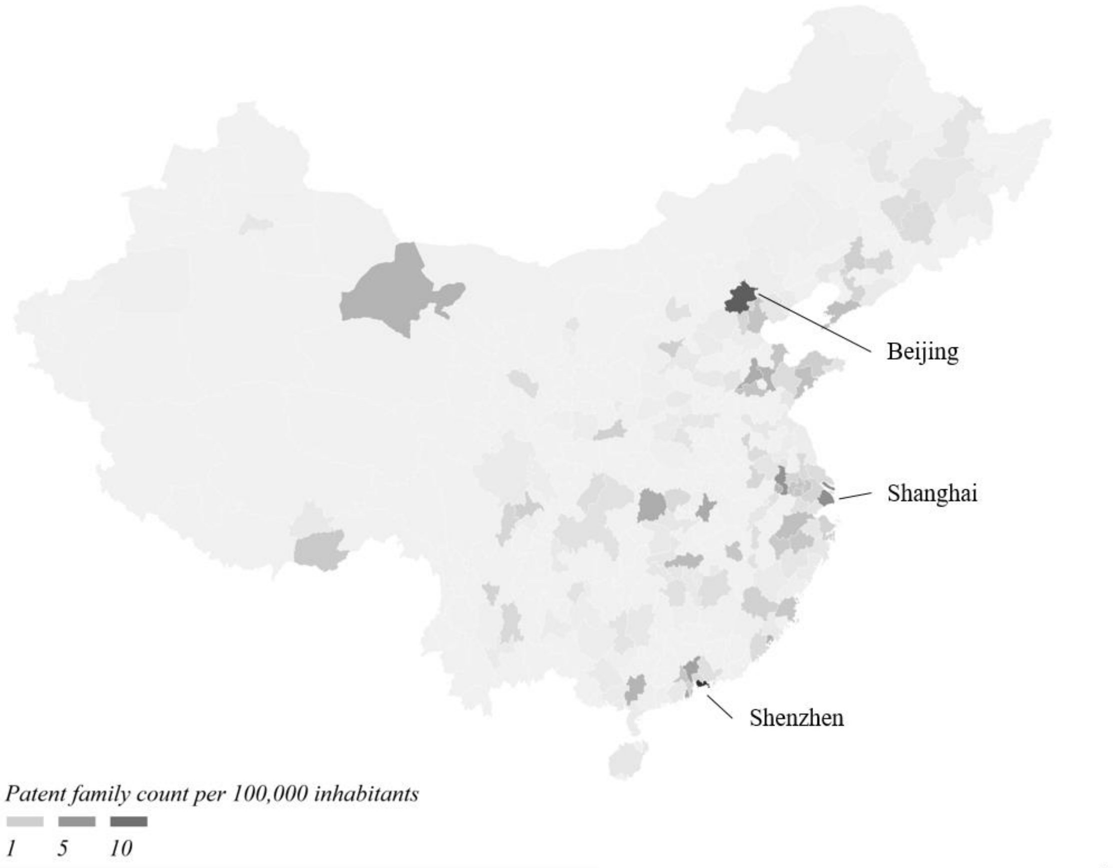
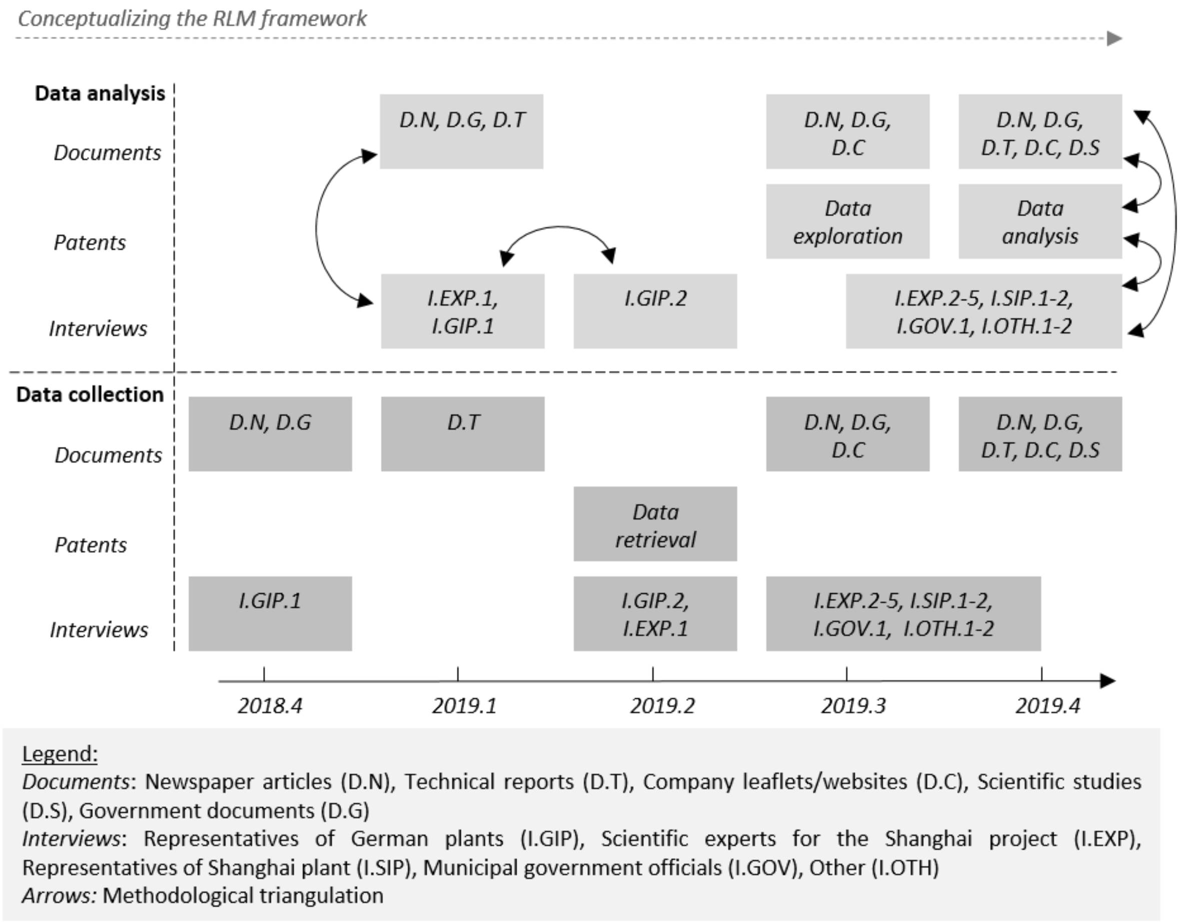


Figure A.2: Waste-related patents in China, patent families from 1970 to 2010 per 100,000 inhabitants, prefecture level
(data: GreenTechDB; Perruchas et al., 2020, Chinese Census 2010)



Legend:
Documents: Newspaper articles (D.N), Technical reports (D.T), Company leaflets/websites (D.C), Scientific studies (D.S), Government documents (D.G)
Interviews: Representatives of German plants (I.GIP), Scientific experts for the Shanghai project (I.EXP), Representatives of Shanghai plant (I.SIP), Municipal government officials (I.GOV), Other (I.OTH)
Arrows: Methodological triangulation

Figure A.3: Flow chart of empirical approach for conceptualizing the RLM framework

Table A.1: Environmental performance of waste incineration plants

Parameter (emissions into air)	Directive 2010/75/ EU	BAT existing plants	BAT new plants	Shanghai I design maximum	Shanghai I actual emission	Shanghai II design maximum
Dust (mg/Nm^3)	10	<5	<5	10	~2	5
HCl (mg/Nm^3)	10	<8	<6	10	~3	10
SO_2 (mg/Nm^3)	50	<40	<30	50	~5	50
NO_x (mg/Nm^3)	200	<150	<120	200	~144	80
CO (mg/Nm^3)	50	<50	<50	50	~5	50
TOC (mg/Nm^3)	10	<10	<10	10	not reported	10
Hg (mg/Nm^3)	0.05	<0.02	<0.02	0.05	not reported	0.05
Heavy metals (mg/Nm^3)	0.5	<0.3	<0.3	0.5	not reported	0.5
Dioxins and furans (ng TEQ/Nm^3)	0.1	<0.1	<0.1	0.1	not reported	0.1

Note: Directive 2010/75/EU of the European Parliament sets legal requirements for waste incineration plants in the European Union and is considered to be the highest environmental standard. China's standards are also based on this directive. The Best Available Techniques (BAT) Reference Document (BREF) for waste incineration by the European Commission explains the best performing technologies for waste incineration and lists achievable emission levels when using such technologies (see Neuwahl et al., 2019). The BREF distinguishes technologies for existing plants and new plants which are yet to be constructed. We thus refer to the BAT for existing plants when evaluating the Shanghai plants. Note that the incineration plant from our case study is listed as 'Shanghai II', while 'Shanghai I' refers to an older plant operated by the same company in the same industrial park. Actual emissions for Shanghai II have not yet been reported. However, design maximum values indicate the maximum emission levels that cannot be exceeded based on the technologies used. Actual emissions for Shanghai II are thus probably considerably lower than design values, especially when comparing both values for Shanghai I. Actual emissions for Shanghai I are calculated as an average of the past two years, using four measurements per day. Note that 'heavy metals' include Sb, As, Pb, Cr, Co, Cu, Mn, Ni and V. TOC stands for total organic carbon. Dioxins and furans include PCDD/F and dioxin-like PCBs. All emission levels refer to daily averages. Slags and bottom ashes of Shanghai II are both recycled and landfilled, equal to processing in Europe.

Table A.2: ENV-TECH classification of environment-related technologies (extended) (Haščič and Migotto, 2015; OECD 2016)

No.	Description
ENVIRONMENTAL MANAGEMENT	
1_1	AIR POLLUTION ABATEMENT
1_2	WATER POLLUTION ABATEMENT
1_3	WASTE MANAGEMENT
1_4	SOIL REMEDIATION
1_5	ENVIRONMENTAL MONITORING
WATER-RELATED ADAPTATION TECHNOLOGIES	
2_1	DEMAND-SIDE TECHNOLOGIES (water conservation)
2_2	SUPPLY-SIDE TECHNOLOGIES (water availability)
CLIMATE CHANGE MITIGATION (ENERGY)	
4_1	RENEWABLE ENERGY GENERATION
4_2	ENERGY GENERATION FROM FUELS OF NON-FOSSIL ORIGIN
4_3	COMBUSTION TECHNOLOGIES WITH MITIGATION POTENTIAL
4_4	NUCLEAR ENERGY
4_5	EFFICIENCY IN ELECTRICAL POWER GENERATION, TRANSMISSION OR DISTRIBUTION
4_6	ENABLING TECHNOLOGIES IN ENERGY SECTOR
4_7	OTHER ENERGY CONVERSION OR MANAGEMENT SYSTEMS REDUCING GHG EMISSIONS
CAPTURE, STORAGE, SEQUESTRATION OR DISPOSAL OF GREENHOUSE GASES	
5_1	CO_2 CAPTURE OR STORAGE (CCS)
5_2	CAPTURE OR DISPOSAL OF GREENHOUSE GASES OTHER THAN CARBON DIOXIDE (N_2O, CH_4, PFC, HFC, SF_6)
CLIMATE CHANGE MITIGATION (TRANSPORTATION)	
6_1	ROAD TRANSPORT
6_2	RAIL TRANSPORT
6_3	AIR TRANSPORT
6_4	MARITIME OR WATERWAYS TRANSPORT
6_5	ENABLING TECHNOLOGIES IN TRANSPORT
CLIMATE CHANGE MITIGATION (BUILDINGS)	
7_1	INTEGRATION OF RENEWABLE ENERGY SOURCES IN BUILDINGS
7_2	ENERGY EFFICIENCY IN BUILDINGS
7_3	ARCHITECTURAL OR CONSTRUCTIONAL ELEMENTS IMPROVING THE THERMAL PERFORMANCE OF BUILDINGS
7_4	ENABLING TECHNOLOGIES IN BUILDINGS
CLIMATE CHANGE MITIGATION (WASTEWATER TREATMENT or WASTE MANAGEMENT)	
8_1	WASTEWATER TREATMENT
8_2	SOLID WASTE MANAGEMENT
8_3	ENABLING TECHNOLOGIES OR TECHNOLOGIES WITH A POTENTIAL OR INDIRECT CONTRIBUTION TO GREENHOUSE GAS [GHG] EMISSIONS MITIGATION
CLIMATE CHANGE MITIGATION (PRODUCTION OR PROCESSING OF GOODS)	
9_1	TECHNOLOGIES RELATED TO METAL PROCESSING
9_2	TECHNOLOGIES RELATING TO CHEMICAL INDUSTRY
9_3	TECHNOLOGIES RELATING TO OIL REFINING AND PETROCHEMICAL INDUSTRY
9_4	TECHNOLOGIES RELATING TO THE PROCESSING OF MINERALS
9_5	TECHNOLOGIES RELATING TO AGRICULTURE, LIVESTOCK OR AGROALIMENTARY INDUSTRIES
9_6	TECHNOLOGIES IN THE PRODUCTION PROCESS FOR FINAL INDUSTRIAL OR CONSUMER PRODUCTS
9_7	CLIMATE CHANGE MITIGATION TECHNOLOGIES FOR SECTOR-WIDE APPLICATIONS
9_8	ENABLING TECHNOLOGIES WITH A POTENTIAL CONTRIBUTION TO GREENHOUSE GAS [GHG] EMISSIONS MITIGATION

Appendix B

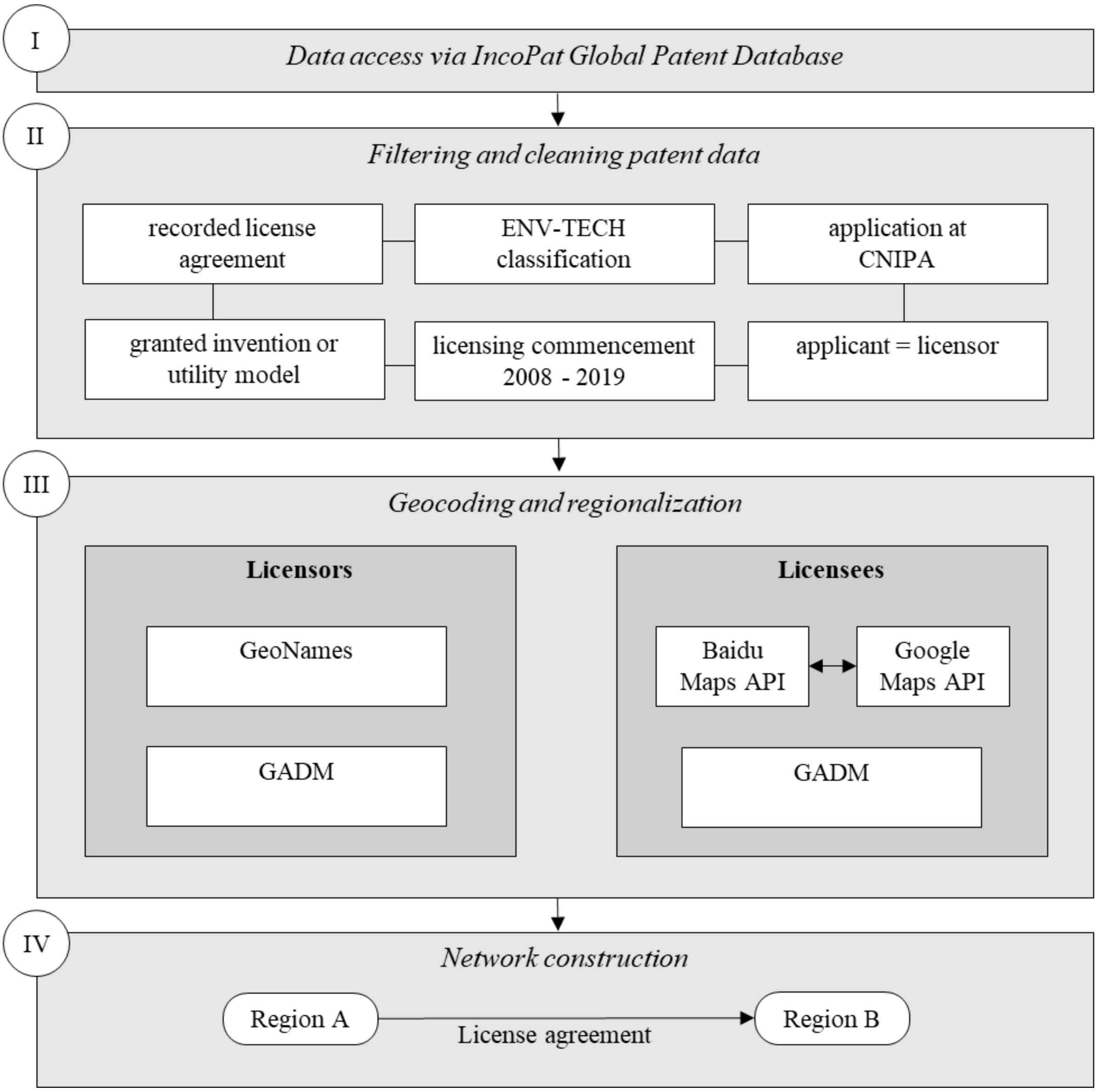


Figure A.4: Overview of processing the green technology patent licensing data

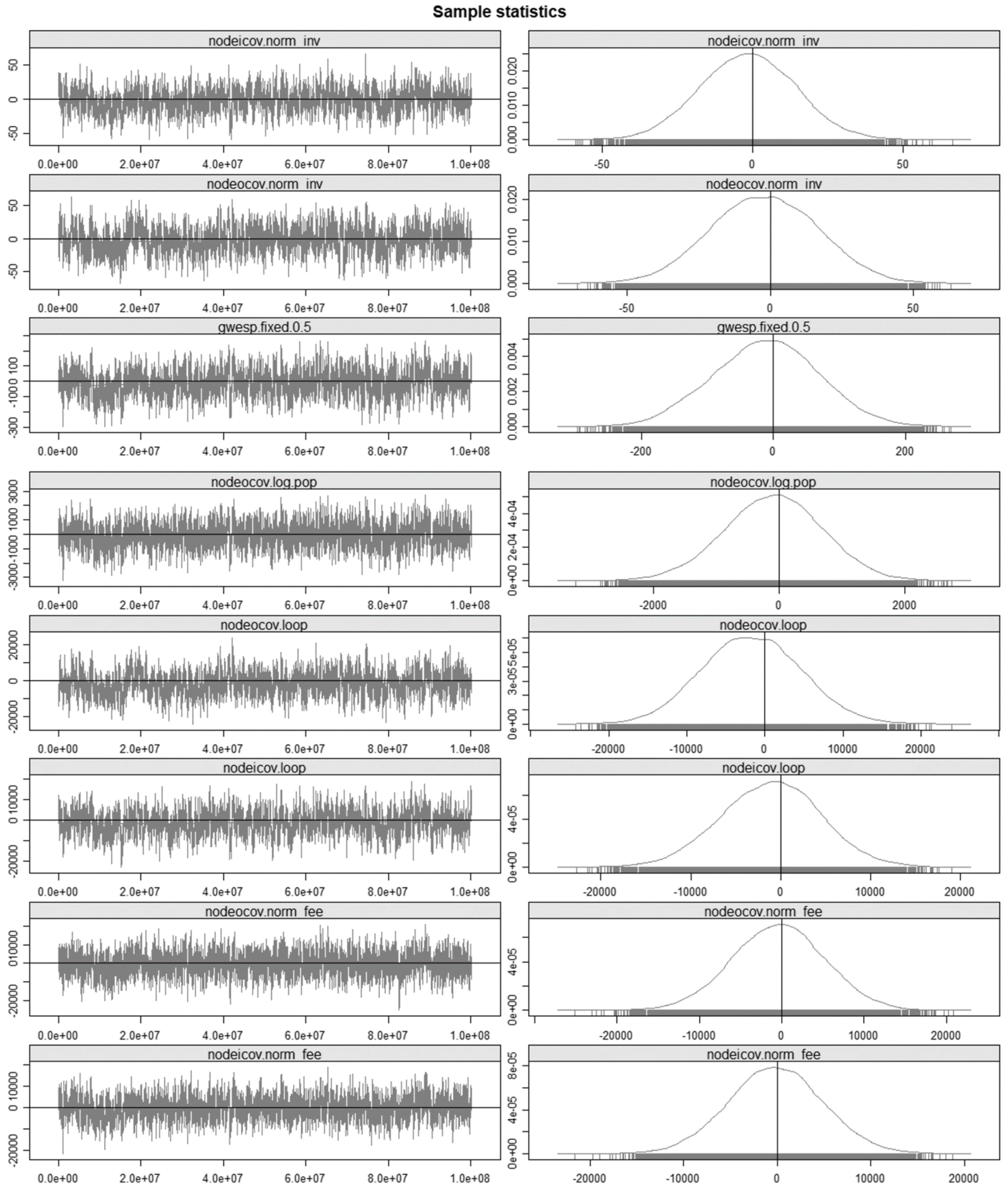
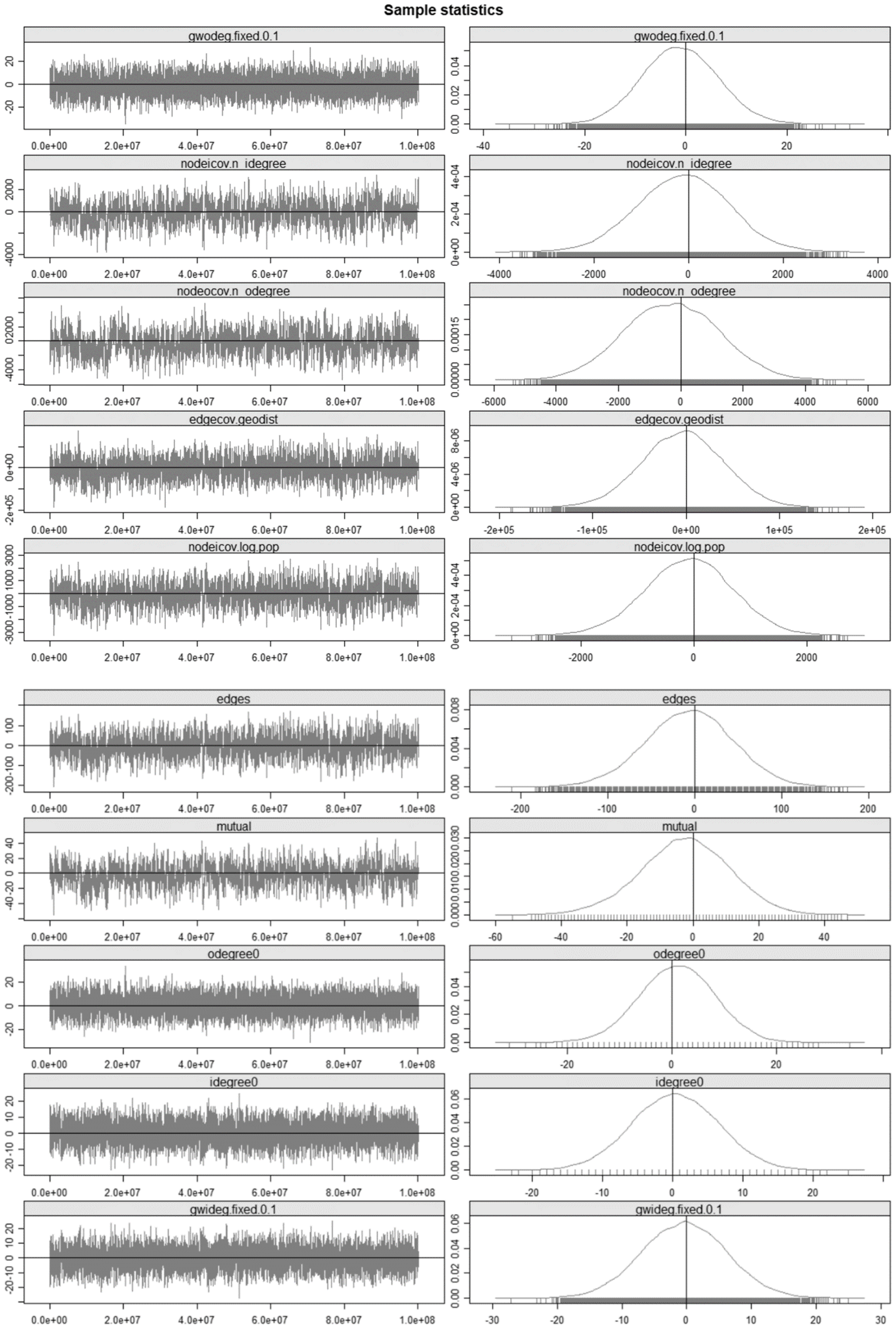


Figure A.5: MCMC diagnostics: trace plots and density plots for sample statistics

Figure A.5: (continued)



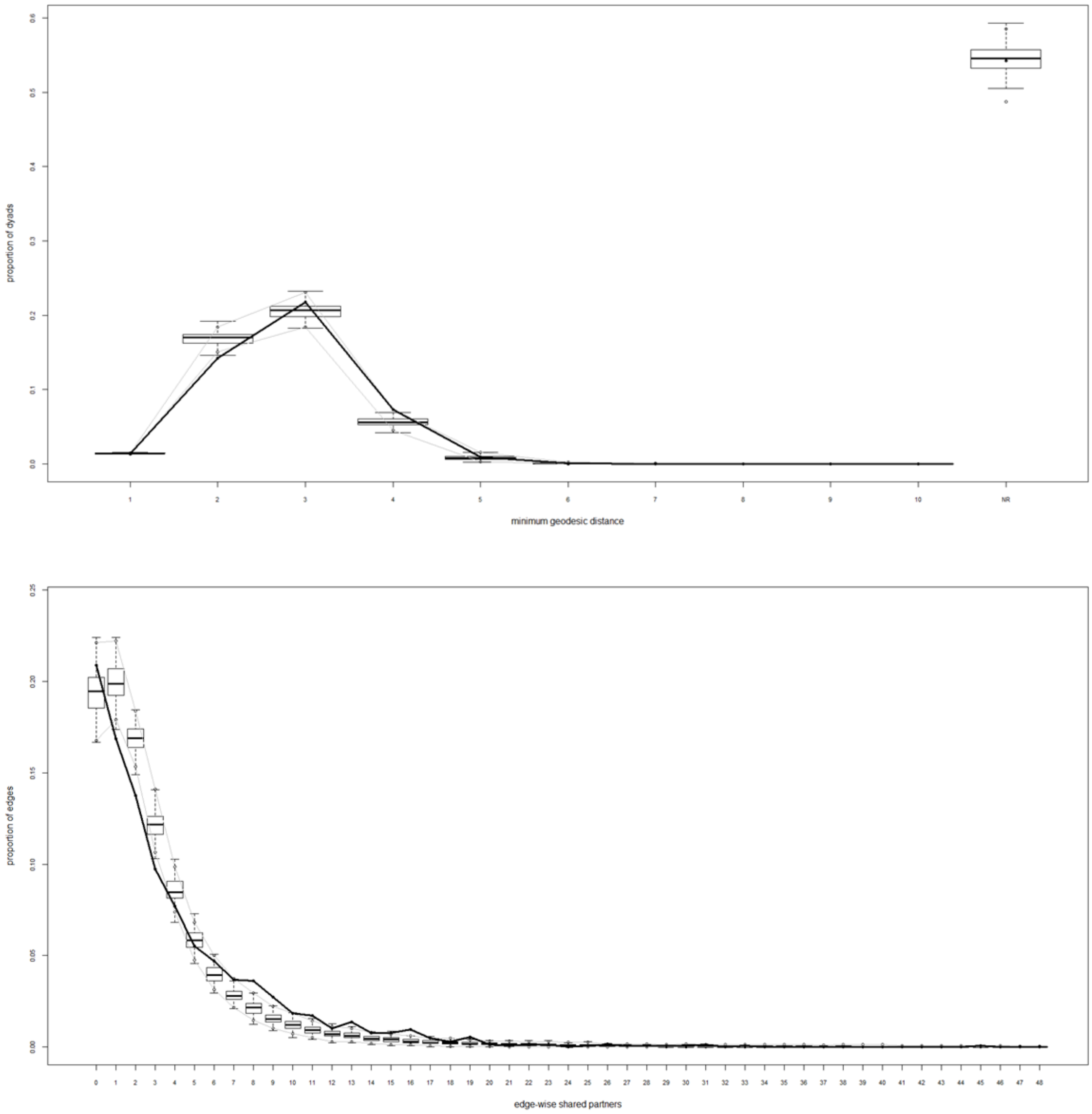
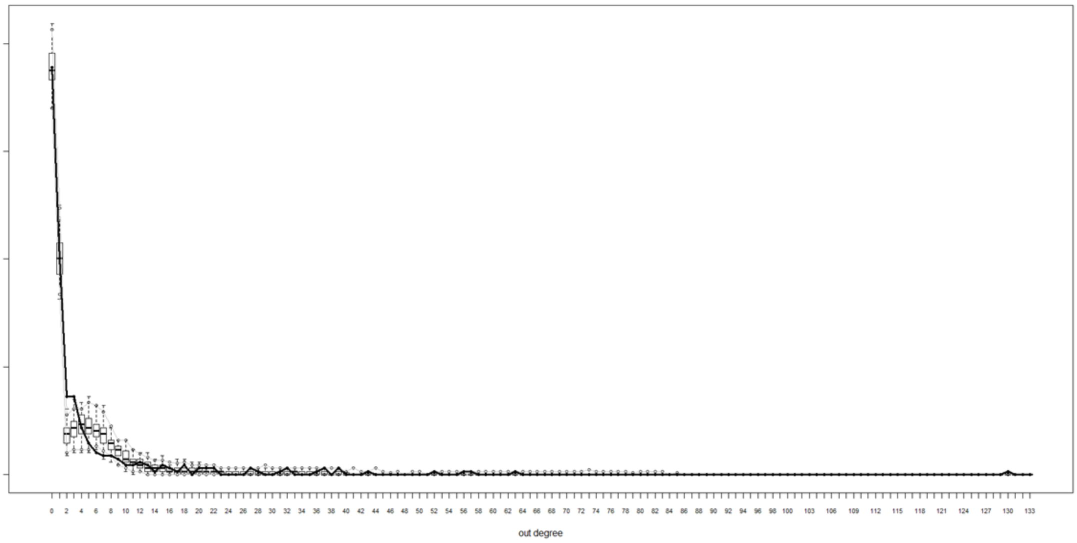


Figure A.6: ERGM Goodness-of-fit diagnostics

Figure A.6: (continued)



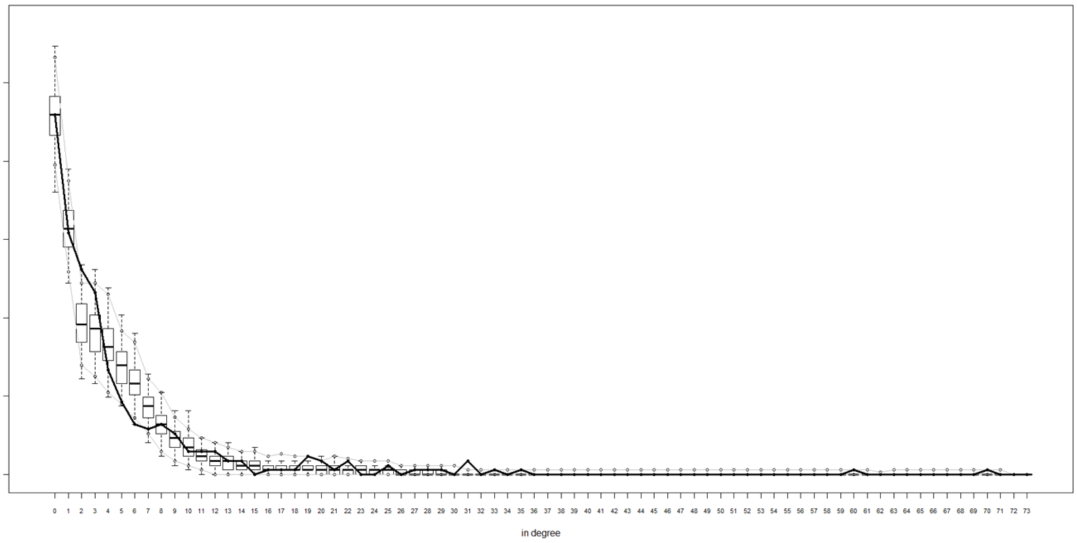


Table A.3: Results of exponential random graph models (robustness checks, all binary)

	(4.4) Tech-domain one		(4.5) Tech-domain four		(4.6) Period one		(4.7) Period two	
	Coefficient	(SE)	Coefficient	(SE)	Coefficient	(SE)	Coefficient	(SE)
EDGES	-14.960***	(0.045)	-19.890***	(0.058)	-14.920***	(0.050)	-16.460***	(0.048)
OUTDEGREE	0.081***	(0.006)	0.253***	(0.018)	0.084***	(0.006)	0.088***	(0.005)
INDEGREE	0.167***	(0.010)	0.154***	(0.012)	0.146***	(0.007)	0.100***	(0.007)
LOOP (in)	-0.008***	(0.001)	-0.016***	(0.002)	-0.006***	(0.001)	-0.004**	(0.001)
LOOP (out)	-0.002	(0.001)	-0.008***	(0.002)	-0.003***	(0.001)	-0.002*	(0.000)
SIZE (in)	0.302***	(0.054)	0.351***	(0.079)	0.259***	(0.052)	0.367***	(0.060)
SIZE (out)	0.373***	(0.053)	0.657***	(0.077)	0.429***	(0.051)	0.448***	(0.059)
INVEST (in)	-0.799***	(0.095)	-0.410*	(0.182)	-0.891***	(0.150)	-0.040	(0.173)
INVEST (out)	-1.469***	(0.142)	-2.583***	(0.294)	-1.692***	(0.167)	-1.982***	(0.197)
FEE (in)	0.001	(0.001)	-0.001	(0.001)	0.000	(0.001)	0.001	(0.001)
FEE (out)	0.002***	(0.000)	0.003***	(0.001)	0.002***	(0.000)	0.003***	(0.000)
GEODIST	-0.001***	(0.000)	-0.001***	(0.000)	-0.001***	(0.000)	-0.002***	(0.001)
MUTUAL	1.235***	(0.162)	1.182***	(0.225)	0.629***	(0.155)	0.875***	(0.169)
GWESP (0.5 fixed)	0.138*	(0.057)	-0.034	(0.063)	0.227***	(0.059)	0.196***	(0.055)
gwidegree(0.1 fixed)	-3.280***	(0.101)	-3.279***	(0.114)	-4.055***	(0.108)	-6.525***	(0.102)
gwodegree(0.1 fixed)	-16.330***	(0.099)	-10.030***	(0.111)	-17.980***	(0.105)	-14.400***	(0.097)
odegree(0)	-14.500***	(0.099)	-8.510***	(0.113)	-16.400***	(0.105)	-13.260***	(0.097)
idegree(0)	-2.576***	(0.101)	-2.124***	(0.115)	-2.950***	(0.107)	-6.300***	(0.102)
AIC	6455		3975		6835		6708	
# license agreements	4275		2314		4695		4701	

Significance. ***p < 0.001, **p < 0.01, *p < 0.05

Note that the geometrically weighted out-degree and in-degree distribution with a decay parameter of 0.1 as well as a static effect for the number of nodes with zero out-degrees and in-degrees were added to assist model convergence in the binary models. *GWESP* is modeled using a decay parameter of 0.5. All Models converged twice. Domain one technologies are related to environmental management, domain four technologies are related to climate change mitigation in the energy sector. Period one contains all license agreements before 2012-05-10, period two contains all license agreements including and after that date (median date).

Appendix C

We conducted several robustness checks to assess the validity of our findings. Firstly, we replaced some variables with alternative indicators. To control for patent complexity, for example, we replaced the number of claims with the technological complexity indicator by Broekel (2019) at the patent level. In addition, instead of using the dummy variable for prefecture-level environmental regulations (*eco_reg*), we used data from the Pollution Information Transparency Index (PITI), which maps the compliance of Chinese regions with environmental transparency regulations (see Brehm & Svensson, 2020). In these specifications, we had to exclude some cases due to missing data. All major results, however, were robust to these changes. Next, following traditional spatial diffusion literature, we controlled for regional hierarchies in additional models, as innovations tend to be adopted in high-ranking regions first (Hägerstrand, 1967). Dummies for the four municipalities with provincial status (Beijing, Tianjin, Chongqing, Shanghai), however, did not affect the results and did not show any significant effect, as hierarchy effects are probably already captured by the other regional variables. As a further robustness check, we controlled for the average technology life cycle stage associated with each patent using the classification by Perruchas et al. (2020), as time-to-adoption might differ between young and mature technologies. However, we do not find any differences and the additional variable does not offer a significant improvement in model goodness-of-fit.

Secondly, we employed different time spans (two, four, five years) instead of three years before each licensing event for all patent-based regional variables as additional robustness checks. Our results are largely robust to these changes, but for some regions the number of patents is too small for short time spans (two years), and for longer time spans (four and five years) we have to exclude more cases due to missing data in the early 2000s. Therefore, we present models with three-year cumulative lags in the results section. Thirdly, we used alternative distributions instead of a lognormal distribution for the hazard function to validate the results of the accelerated failure time models. Log-log and generalized gamma AFT models show similar results, but a poorer goodness-of-fit. Other distributions such as Weibull or exponential do not fit our empirical data. All robustness tests and statistical outputs are available from the authors upon request.

Table A.4: Results for lognormal accelerated failure time models on time-to-adoption (robustness check using clustered SE)

	(5.8a) Inter-regional licensing, licensee region, all patents (cf. 5.4a)	(5.8b) Inter-regional licensing, licensor region, all patents (cf. 5.5a)	(5.8c) Intra-regional licensing, all patents (cf. 5.6a)	(5.8d) Intra-regional licensing, all patents (cf. 5.7a)
green_lic_in	-0.0168		0.0343	
	(0.0565)		(0.0301)	
green_lic_out		0.0947***		0.0182
		(0.0325)		(0.0227)
inno	0.0011	-0.0114***	-0.0102**	-0.0093**
	(0.0038)	(0.0036)	(0.0040)	(0.0037)
rpa	0.0006	-0.0011**	-0.0012**	-0.0012**
	(0.0004)	(0.0006)	(0.0005)	(0.0005)
eco_reg	0.0483	-0.0072	-0.0464	-0.0447
	(0.0300)	(0.0292)	(0.0336)	(0.0347)
pop	-0.0182	0.0238	0.0915***	0.0902***
	(0.0251)	(0.0267)	(0.0309)	(0.0313)
pop_dens	-0.0286	0.0075	-0.0001	0.0010
	(0.0234)	(0.0212)	(0.0199)	(0.0200)
dist	0.0074***	0.0071***		
	(0.0019)	(0.0020)		
util	-0.7179***	-0.7200**	-0.6440***	-0.6441***
	(0.0263)	(0.0404)	(0.0276)	(0.0278)
Patent-licensing controls	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes
Green domain dummies	Yes	Yes	Yes	Yes
Frailty	No	No	No	No
Constant	7.4979***	6.6799***	5.8600***	5.8751***
	(0.3769)	(0.3964)	(0.3930)	(0.4026)
Log(Scale)	-0.6024***	-0.6061***	-0.5660***	-0.5663***
	(0.0254)	(0.0242)	(0.0177)	(0.0177)
Observations	3502	3600	5353	5353
Log-Likelihood	-26732***	-27496***	-40416***	-40416***

Notes: Regional clustered standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$,* $p < 0.1$. The AFT models do not assume the proportionality assumption; the hazard functions follow a lognormal distribution. Negative (positive) coefficients indicate an accelerating (decelerating) effect on the time before a patent is licensed. The natural exponent of a coefficient gives the acceleration factor (i.e. time ratio). Patent-licensing controls (ipc, claims, fwd_cit, indiv, uni, excl) not reported. Models use regional clustered standard errors instead of shared frailty terms.

Short Curriculum Vitae

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2019-2022	Leibniz University Hannover (PhD in Economic Geography)

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List of Publications

Losacker, S. (2022). 'License to green': Regional patent licensing networks and green technology diffusion in China. *Technological Forecasting & Social Change, 75*, 121336. https://doi.org/10.1016/j.techfore.2021.121336

Losacker, S., Hansmeier, H., Horbach, J., & Liefner. (2021). The geography of environmental innovation: A critical review and agenda for future research (*Papers in Innovation Studies* No. 2021/15).

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