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Green Growth in the Technology Space – Regional Diversification Pathways in Europe

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Abstract

Green growth as a way to reconcile economic and environmental benefits, challenges economies to develop capabilities that allow for handling of complex situations. Although an empirical account of these capabilities and their dynamics over time is desirable, current approaches in Evolutionary Economic Geography fall short in systematically accounting for those, in particular at the regional level. The central issue is the need to explore differences and similarities in possible pathways towards green growth in different geographical context. In particular, catch-up regions, which have developed the required capabilities both faster and more successfully, can provide a promising blueprint.

Thus, to examine and contextualize green growth at the regional level, two research questions are addressed: "*Which European regions have successfully diversified into more complex green technological capabilities over time? What are the similarities and differences between catch-up regions with regards to their green growth diversification pathways in the technology space?*"

To answer this, a quantitative-exploratory research approach was followed. Using green patent data, as a first step, a green fitness ranking of regions was developed. From the ranking evolution, a diverse set of leading and catch-up regions were identified according to their general innovation capacity. As a second step, the green technological dynamics over time were mapped out for each catch-up region using the technological relatedness within the regional technology space and observing the patterns over time against the technological dimensions of complexity, relatedness, and technology life cycle.

The analysis confirms general patterns of regional development and path-dependence also for green growth, while the most successful catch-up regions systematically deviate from this. Based on the exploratory mapping, similarities and differences were derived as propositions for green growth diversification pathways. As such, *path upgrading* and *path diversification* are the most feasible, while successful *path development* might potentially be enabled by a dense core or constrained by dense clusters. Mechanisms for pathways include leveraging on technologies at advanced life-cycle stages and thus profiting from extra-regional knowledge, as well as coupling more unrelated *path diversification* opportunities with more related ones in clusters. These mechanisms are particularly interesting for regions with lower innovation capacity.

Contributing factors for more complex green capabilities are strategic technological exits, also as part of re-orientating the portfolio, as well as a stable set of low-complex technologies as anchor points. These insights can inform more effective policy design for green growth, in particular smart specialization strategies.

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1 Introduction

The transition towards the green economy has become a prominent topic for policymakers at all levels, with especially ambitious targets set in Europe by the European Commission. This shift towards a green economic model however requires structural changes, which have the potential to alter the competitive landscape and may have important implications for future economic development of countries and regions alike (Fankhauser et al., 2013). For some economies, this shift may require the phase-out of existing specializations in fossil-fuel based industries and a re-orientation towards more sustainable technologies, such as a turn towards electric vehicles for the German automotive industry; whereas for others it may mean the potential for entirely new economic growth models, such as the substantial, largely untapped and cost-competitive renewable energy potential of South East Europe (IRENA, 2017).

Thus, the structural changes required to reconcile the environmental benefits of greening the economy with potential opportunities for future economic growth can differ substantially between economies; in particular due to the presence, quality and interaction of skills, technologies, physical resources, markets, institutions and policies (Capasso et al., 2019). The implications of these findings are that 1) green growth requires capabilities that allow for handling of complex and non-routine situations among economic actors, 2) technological progress should be directed towards greener technologies, 3) opportunities and challenges for green growth might require different policy rationales and 4) different contexts entail different possible pathways towards green growth at different geographical scales (Capasso et al., 2019).

These implications raise important theoretical and practical questions related to green growth, particularly in terms of how to develop capabilities to handle these more complex situations, to select green technologies and to design supportive policies, given the geographical context.

While a comprehensive study that synthesizes all those questions is still absent, the literature in Evolutionary Economic Geography (EEG) can provide initial insights and guide further research with regards to green growth. A first insight related to the capabilities of an economy can be derived from research in economic complexity. By using the product or technology space as a proxy for the underlying, yet unobservable capabilities that are required to produce those products and technologies it is found that more complex economies are the ones with higher degrees of diversification across the product or technology space. Importantly, higher complexity has been linked to higher potentials for economic growth in the future (Hidalgo et al., 2007; Hidalgo & Hausmann, 2009). Several studies have used these ideas and applied them to green technologies, finding that green products are on average more complex (Mealy & Teytelboym, 2020) and that only very few countries have been able to systematically increase the complexity of their product or technology space due to the inherent difficulty of adding more complex economic activities to their portfolio (Mealy & Teytelboym, 2020; Sbardella et al., 2018).

Moreover, the question of how economies can develop more capabilities in general has been studied extensively in EEG. Empirical patterns of the so-called branching processes were found to be not random, but to follow a path- and place-dependent structure: economies are thus more likely to diversify into products, technologies or industries that require similar capabilities to those that are already present in the economy (Boschma et al., 2013; Neffke et al., 2011; Hidalgo et al., 2007). This has been captured by the "principle of relatedness" in economic geography (Balland et al., 2019). In general, this pattern has also been found to hold for green diversification possibilities of regions (Tanner, 2014; 2016; van den Berge & Weterings, 2014; Santoalha & Boschma, 2019). Others have provided a more nuanced picture, for instance showing that unrelated variety, a regional measure of the degree of diversification, is more important in early stages of the green technology-life cycle, while related variety becomes more important along the maturity path (Barbieri et al., 2020).

These insights have recently been used as a framework for smart specialization strategies in the EU (Balland et al., 2019). This policy approach focuses on European regions and its main idea is to encourage regions to leverage on their relative strengths in terms of local capabilities, to avoid imitation and direct competition with other European regions (Foray et al., 2011). The aim is to develop place-specific competitive advantages in high value-added activities in particular (Whittle & Kogler, 2020). This however gives rise to a so-called "diversification dilemma". While the policy approach pushes regional actors to seek out more complex knowledge opportunities, most regions lack the diversity of capabilities required to derive more complex knowledge (Balland et al. 2019). The recommendation to overcome this dilemma is to develop the existing knowledge cores further and expand the capabilities following the "principle of relatedness" towards more complex technologies (Balland et al., 2019).

While tentative answers can thus be derived also for the green economy, important questions in the context of green growth remain underexplored in this research direction. The central issue is that there is a need to explore the differences and similarities in possible pathways towards green growth in different geographical contexts (Capasso et al., 2019). The tendency in empirical EEG research to average effects across countries and regions with highly divergent capabilities has so far limited the possibilities of exploring the diversity of successful diversification pathways, and the underlying technological and regional factors, in more detail; the importance of which was for instance shown by investigating the effects of relatedness at different stages of the green technology life cycle (Barbieri et al., 2020).

Systematically accounting for this variety in the green economy holds a compelling promise: regions can reconcile their individual future economic growth paths with the collective environmental advantages of the produced green technologies, if they are able to better identify diversification opportunities in more complex green technologies according to their technological and regional contexts. In particular, observing the pathways of so-called catch-up regions, which have developed the required capabilities both faster and more successfully than other regions, can provide a blueprint for similar regions in directing them to develop such capabilities.

Thus, to examine and contextualize green growth at the regional level, this thesis aims to answer two research questions:

RQ1: Which European regions have successfully diversified into more complex green technological capabilities over time?

RQ2: What are the similarities and differences between catch-up regions with regards to their green growth diversification pathways in the technology space?

The first research question is answered by providing a ranking of European regions based on the complexity of their green technological capabilities and their evolution over time and reflecting the results against previously developed regional innovation typologies (European Commission, 2014; OECD, 2011b; Wintjes & Hollanders, 2010) to account for differences in the general innovation capacity of European regions. Based on this, the European Green Fitness Leaders are identified as those top performers against regions with similar innovation capabilities and the European Green Fitness Catch-ups, as those that have been particularly successful in climbing the ranking towards more complex green technologies over time.

The second research question is answered by exploring the technological dynamics of entry, exit and remaining green technologies in the regional technology space over time and discussing the role of technological complexity, relatedness, the technology life cycle and the regional innovation capacity for their green growth diversification processes. To get as diverse contextual insights as possible, Catch-up regions from different typologies are selected.

Overall, this research approach holds promise with regards to the research agenda for green growth set out by Capasso et al. (2019). Most importantly, it identifies which regions possess the capabilities to thrive in the green economy and provides an account of the diversity of possible pathways towards green growth in different regional contexts. Furthermore, by understanding which green technology pathways regions have taken, insights for green growth policies at the regional level can be derived.

The thesis is organized as follows: Chapter 2 provides an overview of the theoretical and conceptual work underlying the green economy and regional diversification pathways. Chapter 3 presents the chosen research approach, selected data and the methods used. Chapter 4 shows the results to the research questions, followed by a summary of the most important findings in Chapter 5. In Chapter 6 the thesis is critically reflected.

2 Theoretical and conceptual background

2.1 The Green Economy

Greening the economy is a multifaceted challenge, involving among others, a variety of environmental and economic goals. The narrative underlying this challenge has increasingly shifted towards a discourse on “green growth”, where governments across the world try to highlight the economic opportunities rather than challenges that arise from pursuing environmental sustainability (Capasso et al., 2019). Consequently, the OECD defines green growth as *“fostering economic growth and development while ensuring that natural assets continue to provide the resources and environmental services on which our well-being relies”* (2011a, p.9).

In a recent review, Capasso et al. (2019) synthesize the debate on drivers and barriers of green growth. By drawing on existing insights from the EEG and Sustainability

Transitions (ST) literature, a particular emphasis on the role of innovation and the spatial development of green industries is placed. Following their argument, the transition towards a green economic model necessitates radical transformations of technologies, associated markets, and institutions and therefore the role of innovation should be explicitly considered. Nonetheless, it is recognized that (technological) innovation is only but one pillar of the green economy and successful green growth strategies have to encompass a set of further supporting elements, which among others include a shift in economic incentives away from utilizing non-renewable natural resources, i.e. making pollution costly and reforming environmentally-harmful subsidies, or in consumer behaviour, i.e. promoting resource-saving behaviours (OECD, 2012).

Consequently, innovation conditions for green growth not only involve the existence and development of technologies but also the presence, quality and interaction of skills, physical resources, markets, institutions, and policies at different spatial scales (Capasso et al., 2019). The synthesis highlights specificities of green growth processes compared to a more traditional understanding of economic growth processes by positing that 1) green growth requires capabilities that allow for handling of complex and non-routine situations among economic actors, 2) technological progress should be directed towards greener technologies, 3) opportunities and challenges for green growth might require different policy rationales and 4) different contexts entail different possible pathways towards green growth at different geographical scales (Capasso et al., 2019).

These implications raise important research challenges for green growth: Which economies possess the capabilities to handle the complex and non-routines situations related to green growth and how can those capabilities be developed? To which green technologies should economies direct their technological progress to? How can policies support the development of both complex capabilities and of green technologies? And how do possible pathways towards green growth differ in different geographical contexts?

While several tentative answers can be derived from the literature in EEG and ST, the major point of concern is the need to explore the differences and similarities in possible pathways towards green growth in different geographical contexts (Capasso et al., 2019). While almost half of the reviewed contributions related to green growth focused on the national level, comparatively little work has been done at the regional level. This however undermines the substantial sub-national variety of green growth processes related to the creation of knowledge, the development of industries and the role of local policy ambitions, which are all strongly embedded in particular cities and regions (Madsen & Hansen, 2018; McCormick et al., 2013). Furthermore, it disregards the presumably varying opportunities for achieving green growth in different types of regions which is in line with the argument that pre-existing industrial specialisations, economic activities and institutional contexts all enable and constrain the possibilities for the greening of existing or the development of new green industries at the regional level (Capasso et al., 2019, Grillitsch & Hansen, 2018; Boschma et al., 2017).

Taking the regional dimension as a point of departure and systematically accounting for the diversity of regional green technology pathways, can thus lead to promising new insights for green growth. Regions could reconcile their individual future economic growth paths with the collective environmental advantages of newly produced green knowledge and the subsequent diffusion of green technologies, if they are able to better identify diversification opportunities in more complex green technologies according to their technological and regional contexts.

To guide this research, the following sub-chapters focus on some of the tentative answers that can be derived from the literature in EEG and ST. As a conceptual basis for understanding which regions possess the capabilities required to handle complex situations, the relationship of technological capabilities and economic complexity is reviewed and discussed in relationship to the green economy (2.2). To understand the development of capabilities over time and the direction of technological progress, the principle of relatedness is reflected (2.3). Furthermore, smart specialisation as a regional innovation approach that combines these insights for the development of more complex capabilities into a policy framework is introduced (2.4). Based on this, a conceptual framework for analysing and contextualizing green growth diversification pathways is proposed (2.5).

2.2 Technological Capabilities and Economic Complexity

The complexity of knowledge in an economy is considered a valuable source of competitive advantage for firms and regions (Asheim & Gertler, 2005; Kogut & Zander, 1992). Simple knowledge can usually be codified and thus easily transferred. More complex knowledge on the other hand is more tacit in nature and is thus deeply rooted in space and time, embedded in routines, interpersonal contacts and local actor networks, preventing an easy transfer (Balland et al., 2019; Balland & Rigby, 2017).

Conceptually however, this raises a fundamental challenge: How to measure and compare the degree of such valuable, tacit knowledge between regions? One way of doing so has been proposed by Hidalgo & Hausmann (2009), who developed the idea of product and place complexity. While the underlying capabilities of an economy cannot be directly observed, the products that are produced and exported by an economy can be understood as a proxy of the range of necessary capabilities that are combined to produce the products. The idea is that the less countries are exporting a given product competitively, the wider the range of capabilities required to make the product, the higher the complexity of the product and consequently of the economy that can produce it.

Using this approach of inferring the complexity of an economy based on the degree of diversification and the contents of the product or technology portfolio has among others been successfully applied to explain divergent patterns of economic development between countries (Hausmann et al., 2014; Hidalgo & Hausmann, 2009), suggesting that more complex economies seem to be better positioned to sustain their competitive advantages in the long run, confirming the spatial stickiness of complex knowledge.

With regards to the green economy and following the recent momentum on researching the determinants of environmental innovations, the topic of complexity has become a key dimension. Given that such innovations have to comply with multiple technical-economic problems (Oltra & Jean, 2005), more stringent regulatory requirements (Carrillo-Hermosilla et al., 2010), are characterized by a lack of standards and are at the forefront of the technological frontier, they often result from the integration of heterogenous and cognitively distant technologies and knowledge sources; also, they are more likely to emerge as the result of collaborative efforts between organizations, research institutions, universities, and teams of inventors. All those aspects require skills different from more traditional capabilities (Fusillo, 2020; Fusillo et al., 2019; Petruzzelli et al., 2011). While the underlying definitions and sources of the inherent complexity of green technologies differ, these findings are consistent with the implication that green growth requires capabilities that allow for handling of complex and non-routine situations among economic actors (Capasso et al., 2019).

In the following, complexity is understood in terms of the ubiquity of each green technology and the diversity of each regional green technology portfolio. Technological complexity is determined by the number of regions that can produce a green technology competitively. The regional economic complexity, which is called the fitness, in turn depends on the technological complexity of each green technology in a regional portfolio (Sbardella et al., 2018). While this approach to complexity remains agnostic towards the sources of complexity, it is nonetheless useful due to its efficiency and has thus been widely used (see i.e. Sbardella et al., 2018 for an overview).

Only few country-level studies have already used such a definition of and approach to economic complexity to study the particularities of green products or technologies. Mealy & Teytelboym (2020) find that green products are on average more complex compared to all other products and therefore require more technologically advanced capabilities. Furthermore, by providing a ranking of the complexity of countries' green product or technology portfolios, and its evolution over time, it is shown that most of the countries remain within the realm of their starting positions in the ranking, with for instance the United States, Germany, Italy and France remaining in the leading group of countries throughout. Consequently, only very few countries, identified as catch-up countries, have been able to systematically increase the complexity of their green portfolios compared to all other countries and thereby considerably improve their ranking position, such as China, Vietnam, Slovakia or Uganda. This points to the inherent difficulty of adding more complex economic activities and suggests a strong path-dependence also with regards to the green economy (Mealy & Teytelboym, 2020; Sbardella et al., 2018).

What is more is that green economic capabilities seem to be closely aligned with economic and environmental measures, suggesting the need to further consider complexity as a relevant dimension of green growth. Higher positioning in the ranking is associated with higher per capita GDP, as well as significantly higher environmental patenting rates, lower CO_2 emissions and more stringent environmental policies (Mealy & Teytelboym, 2020). This indicates the possibility of aligning individual green economic growth paths with collective environmental advantages of following those. In turn, noticing the highly industrialized economies at the top of the ranking, this might also suggest that for economies with lower GDP, less stringent environmental policies and less (environmental) patenting rates, it might be very difficult to access those green growth paths, suggesting the need to further disentangle contextual dimensions of such an analytical approach to look at the diversity of possible pathways, according to for instance the general innovation capabilities of an economy. This might also help to explain why some countries managed to catch-up, while others did not.

Nonetheless, developing more complex green products or technologies seems to be attractive, due to the proposed high and long-term economic benefits which can be derived from those. On the other hand, developing the necessary complex capabilities is also not without its risks. By its very definition, complex capabilities are very difficult to obtain due to the higher uncertainty and higher costs involved compared to more simple capabilities that are found widely in different economies (Hidalgo et al., 2018). Thus, to better understand how more complex capabilities can be developed for the green economy, it is important to understand how capabilities are generally observed to develop over time and the regularities of technological progress.

2.3 The Principle of Relatedness

The question of the spatial formation of new economic capabilities has been studied in EEG by drawing on notions of path-dependence, lock-ins, path-renewal, and path-creation of regional economies (Hassink, 2010; Martin & Sunley, 2006). It is argued that spatial capabilities provide opportunities but also set limits for developing new industrial opportunities (Xiao et al., 2018). In the following, relatedness is understood as the spatial co-occurrence of technologies, such that the more often technologies are co-produced in the same regions, the more related they are; underlying this is the assumption that being successful in producing both technologies would probably require similar, yet unobservable capabilities. Based on this idea, a technology space, as a network-based representation of the relatedness between all technologies can be derived, where related technologies are in close proximity and connected, whereas unrelated technologies are distant and unconnected (Balland, 2016).

The main point is that economies are more likely to diversify into new economic activities that are closely related to the pre-existing economic structure, because they can draw on and exploit similar underlying capabilities; these diversification processes can be conceived as an emergent branching process (Boschma & Frenken, 2011; Frenken & Boschma, 2007). This means that in their technology space, they are more likely to move towards proximate and connected technologies. The mechanisms underlying these emergent branching process can have very different starting points, ranging from firm diversification (Tanner, 2014), labour mobility (Neffke et al., 2011), actor networks within regions (Breschi & Lissoni, 2009) or entrepreneurial spinoffs (Boschma & Wenting, 2007). Despite differences in the applied relatedness measure, the dependent variable, spatial unit of analysis and the time period in empirical studies, there is strong systematic evidence that the existing set of local capabilities conditions which new economic activities are more likely to emerge in regions (Boschma, 2017). In general, the strong positive effect of relatedness on the development of new green activities in an economy holds true (Santoalha & Boschma, 2019; van den Berge et al., 2019; Montresor & Quatraro, 2019; van den Berge & Weterings, 2014).

While related diversification is thus more dominantly observed in terms of new industries (Neffke et al., 2011; Boschma et al., 2013) and new technologies (Kogler et al., 2013, Feldman et al., 2015), unrelated diversification processes can also be successful. Isaksen & Trippl (2014) have described this in terms of regional growth paths, distinguishing between path renewal through related and new path creation through unrelated diversification. A number of studies have considered the differences of related and unrelated branching processes and found that unrelated diversification is more likely in high-income countries (Petralia et al., 2016), liberal market economies (Boschma & Capone, 2015) and Western European regions compared with Eastern European regions (Boschma & Capone, 2016). In line with this, Xiao et al. (2018) have found that the effect of relatedness on new industrial specialization decreases with the increase of a region's general innovation capacity, as there are more possibilities for regions to deviate from their path-dependence. On the other hand, relatedness still plays a more important role in knowledge-intensive industries (Xiao et al., 2018).

Therefore, the principle of relatedness seems to be dependent on the regional and technological context. For the green economy, studies that have considered the effects of both related and unrelated variety argue that due to the higher complexity of green technologies, they require the recombination of more distant pieces of cognitively distinct knowledge (Santoalha & Boschma, 2019; Quatraro & Scandura, 2019). Therefore, the effect of relatedness is more nuanced along the green technology life cycle, such that unrelated variety plays a more important role in the early stages, while related variety becomes more important along the maturity path of the technology (Barbieri et al., 2020). Overall, unrelated variety has a stronger effect on the development of green economic activities (Barbieri et al., 2020; Barbieri & Consoli, 2019), also due to the fact that green technologies are more often at an early stage of development in the lifecycle (OECD, 2015).

Besides this more nuanced picture of the green technology lifecycle, studies that have explicitly considered relatedness in the green product space argue that the green products with the highest growth potential are also the ones most related to a countries' existing economic structure (Fraccasia et al., 2018), which in turn leads to recommendations about green diversification opportunities for individual countries based on the set of most related products in their green product space (Mealy & Teytelboym, 2020). The implication of those arguments is thus that following the principle of relatedness can provide guidance towards which green technologies economies should direct their technological progress to.

On the other hand, the tendency in empirical EEG research to average effects across countries and regions with highly divergent capabilities has so far limited the possibilities of exploring the diversity of successful diversification pathways, and the underlying technological and regional factors, in more detail; the importance of which was for instance shown by investigating the effects of relatedness at different stages of the green technology life cycle (Barbieri et al., 2020) or when accounting for the general regional innovation capacity (Xiao et al., 2018). Additionally, these studies have mainly considered relatedness within the subset of green products or green technologies rather than across the whole technology space; due to the heterogenous and cognitively distant combination of knowledge that underlines the development of green technologies however, providing a more complete picture is desirable.

Thus, the question of whether the particularly successful catch-up regions in the green economy have developed these more complex capabilities over time by following the principle of relatedness or by deviating from it and under which conditions, deserves more empirical attention. Critically reflecting the role of relatedness in 1) different types of regions in terms of their innovation capacity 2) for different degrees of technological complexity, and 3) across the technological life cycle could allow for more targeted green diversification opportunities in regional technology spaces.

2.4 Smart Specialization Strategies

Taking the particularities of green technology diversification into account is an important aspect also in terms of more targeted regional innovation policy. By understanding which green technology pathways, the particularly successful catch-up regions have taken, insights for green growth policies at the regional level can be derived. In particular, it might be informative with regards to smart specialization strategies for societal challenges, particularly those related to climate change.

Against the background of the previously discussed concepts of complexity and relatedness, smart specialization has recently emerged to support regional policy under the European Cohesion targets as part of the EU2020 strategy (Piirainen et al., 2017). The main idea is that European regions are encouraged to identify their relative strengths and leverage on them in the future to avoid duplicating, imitating, or competing with other European regions (Foray et al., 2011; McCann & Ortega-Argilés, 2013). Consequently, regions should focus on developing place-specific competitive advantages in high value-added activities in particular to capture future economic growth possibilities (Whittle & Kogler, 2020; Balland et al., 2019).

By suggesting a complexity-relatedness framework, these ideas are formalized to provide guidance for the direction of future technological progress. While relatedness reduces the risks, complexity influences the potential benefits of diversification possibilities. Consequently, "smart" specialization is primarily understood as the expanding the capabilities through related technologies in the direction of more complex technologies (Balland et al., 2019).

While this synthesis of empirical regularities seems appealing, several problems remain. First, the rather universal definition of what constitutes "smart" in smart specialization might prevent regions in developing their place-specific approach (Whittle & Kogler, 2020). For instance, the evaluation of diversification risks and benefits could change if several green technologies could be subsequently accessed after just one initial unrelated diversification step; or again, with the general innovation capacity of a region. This would suggest that different configurations of branching opportunities along the complexity-relatedness space exist that might warrant a stronger focus on unrelated diversification. This is in line with the previously described need to critically reflect the role of relatedness in different types of regions, for different degrees of technological complexity and across the technological life cycle.

Secondly, the framework is largely agnostic about societal challenges, such as curing cancer or greening the economy. While Foray (2018) has argued for its compatibility with such endeavours, Hassink & Gong (2019) have called for a better understanding of potential trade-offs between economic competitiveness and other aspects of social well-being. This is strongly connected with third, the justification for policy intervention in the framework as it concerns the additionality requirement. The argument is that if related diversification and path-dependency is a strong driver on its own, then the role of policy might rather be to provide the conditions for deviating from this pattern (Frenken, 2016). This is also in line with the implication that opportunities and challenges for green growth might require different policy rationales (Capasso et al., 2019). For instance, understanding the green growth challenge in terms of a transformational system failure might fundamentally alter the evaluation of diversification risks and benefits related to smart specialization.

While exhaustive answers to those theoretical challenges are outside the scope of the chosen research approach, providing empirical insights into the green diversification pathways of particularly successful catch-up regions in the past, could provide some indication into differences of potential branching opportunities within the complexity-relatedness framework. In turn, this could be informative with regards to place-specific smart specialization approaches in particular for the green economy.

2.5 Contextualizing Green Growth Diversification Pathways: the influence of technology life cycle and regional innovation capacity

Based on the theoretical discussion, a conceptual framework for analysing and contextualizing regional green growth diversification pathways is proposed. What becomes clear is that there is a need to shed light on the diversity of successful green diversification pathways at the regional level, as previous approaches have limited the possibilities of exploring and comparing those pathways according to regional and technological context (Capasso et al., 2019; Boschma, 2017). Nonetheless, several initial conceptualizations have already been proposed (Grillitsch & Hansen, 2019; Boschma et al., 2017; Piirainen et al., 2017). While those frameworks are not explicitly tested, they provide a good starting ground for the empirical research setting of this study.

As a first dimension, the complexity of green technologies is considered, as more complex regional green technology portfolios are associated with higher and more long-term economic benefits. These individual economic benefits might in turn incline regions to follow green growth diversification pathways and align these with the collective benefits that would be derived from developing more green technological capabilities and technologies.

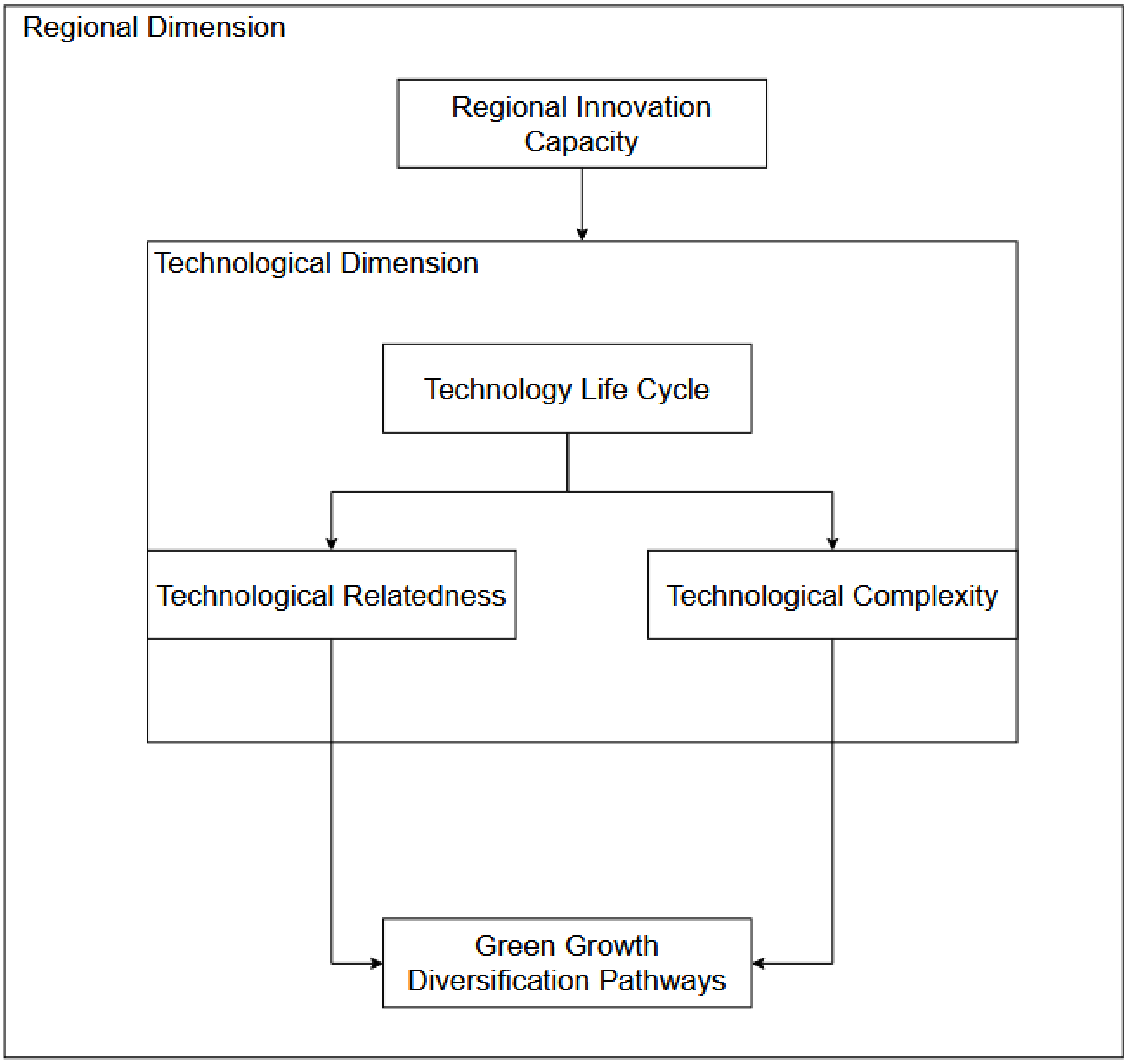
As a second dimension, the relatedness of green technologies within the technology space is considered. As diversification processes at the regional level are known to exhibit a strong path-dependence, also for green technologies, relatedness can provide guidance in achieving more complex regional green technology portfolios. On the other hand, the question is whether the particularly successful catch-up regions have achieved their more complex green capabilities by following the principle of relatedness particularly closely, or by deviating from it and if so, under which conditions. To study this, two more contextual dimensions are introduced: the green technology life cycle and the regional innovation capacity.

For the green technology life cycle, Barbieri et al. (2020) have shown that unrelated variety is more important in early stages of the cycle, while related variety becomes more important along the maturity path. They distinguish between 4 stages of the technology life cycle, based on the geographic concentration of patenting activities and the patenting output: the emergence stage, with high concentration and low patent numbers, followed by either the development stage, with increased patenting output or the diffusion stage, with more regions engaging in patenting activities. The last stage is maturity, where technological standardisation is achieved, and output and geographic diffusion are high. Considering this additional context could lead to novel insights, i.e. if the maturity of technologies facilitates unrelated regional diversification processes as regions can rely on more established knowledge developed outside of the region.

For the regional innovation capacity, Xiao et al. (2018) have found that the effect of relatedness on new industrial specialization decreases with the increase of a region's general innovation capacity, as there are more possibilities for regions to deviate from their path-dependence. In line with this, Grillitsch & Hansen (2019) distinguish between four types of regions in highlighting available pathways for green technology development. For peripheral regions who are constrained in their innovation support systems and in their existing industrial capabilities, green pathways are limited to 1) path emergence of a green industrial specialization, by for instance drawing heavily on extra-regional knowledge and resources and to 2) path upgrading from for instance low-skill manufacturing in green industries to more value-added activities in the same industry. For metropolitan regions, with strong and comprehensive innovation support systems and a mix of industrial specializations, additional pathways involve 3) path development, by e.g. introducing new technologies for existing green industries, and 4) path diversification into either related or unrelated green industries. Specialized regions, depending on their situation, could follow one of the four ideal-typical pathways. Thus, both the existing green capabilities and their relationship within the industrial composition of the region, but also the general innovation capacity could constrain or enable the available strategies for green technology development and potentially influence the effects of relatedness.

Taken together, the conceptual framework for analysing and contextualizing regional green growth diversification pathways is proposed in Figure 1.

Figure 1: Conceptual Framework - Regional green growth diversification pathways



3 Data and Methods

3.1 Research approach

The chosen research approach for this thesis is best described as quantitative-exploratory, largely in line with what was proposed by Qi et al. (2020). In so doing, it seeks to combine and provide a bridge between the quantitative literature in EEG and its established methods of understanding complexity and relatedness (such as Mealy & Teytelboym, 2020; Balland et al., 2019; Sbardella et al, 2018; Boschma et al., 2015; Hidalgo et al., 2007), with the logic of the more conceptual, qualitative case-study approaches of the regional pathway literature (i.e. Grillitsch & Hansen, 2019; Isaksen & Trippl, 2014; Hassink, 2010). This research approach is largely inspired by several contributions that have used the idea of studying the product space and its evolution to recommend further diversification opportunities, such as Qi et al. (2020), for the maritime economy in the Chinese product space, or Hamwey et al. (2013) for green opportunities in Brazil. Nonetheless, these contributions have not systematically discussed the dynamics of the product space evolution of entries, exits and remaining technologies against spatial and technological dimensions.

Overall, this quantitative-exploratory account was seen as most appropriate to allow for the study of the considerable dynamics related to the contextualization of 1) the regional dimension, 2) the technological dimensions and 3) the time dimension for green growth. While it is recognized that some recent contributions have indeed considered contextual dimensions such as He & Zhu (2019), who studied the catch-up behaviour in developing regions by looking at extra-regional linkages, firm agency, institutions and policy making using regression analysis, the attempt here allows to capture more of the nuances of the diversity of green growth diversification pathways and draw insights from a rather small selection of particularly successful catch-up regions only.

3.2 Green patent data

Throughout the study, patent data was used to answer the research questions. Patent data is usually considered an appropriate proxy to capture the regional technological capabilities albeit not without limitations, such as that they are not uniformly distributed across sectors and favour large firms (Whittle et al. 2020; Kogler, 2015). The data was collected from the OECD REGPAT database which regionalizes all patent applications to the European Patent Office (EPO) (OECD REGPAT database, January

2020). For the analysis, the inventor address was used, as it is argued that it better represents the location of the inventive capabilities than the applicant address (Kogler et al., 2017).

To identify the green technology patents, the CPC classification of sustainable technologies is utilized, which as of 2018 involves 9 different sub-classes of technologies, ranging from Adaptation to climate change (YO2A) to Industry and agriculture (YO2P), Transportation (YO2T) and Smart Grids (Y04S). To provide a more detailed account of the green technologies, all patents were aggregated at the 8-digit main group level. An overview is provided in Table 1.

Table 1: Overview of Green Technology Patenting

	Green Technology Class	**# Main groups**	**1995-1999**	**2000-2004**	**2005-2009**	**2010-2014**
Y02A	CC Adaptation Technologies	24	1412.15	2074.86	2877.06	2557.62
Y02B	CCMT Buildings	36	994.85	1368.79	2459.42	3118.62
Y02C	GHG Capture, Storage, Sequestration or Disposal	11	124.93	163.65	335.4	401.18
Y02D	CCMT Information and Communication Technologies	18	300.83	642.87	959.39	1554.86
Y02E	GHG Reduction Energy Generation, Transmission or Distribution	30	1587.17	2868.96	7408.36	10179.06
Y02P	CCMT Production or Processing of Goods	38	2452.53	3249.36	4296.63	5116.12
Y02T	CCMT Transport	21	2288.87	3881.18	6023.86	8178.49
Y02W	CCMT Wastewater Treatment or Waste Management	12	1171.12	1091.58	1285.41	1412.25
Y04S	Systems Integrating Technologies, i.e. Smart Grids	15	93.9	143.52	289.23	510.71
		205	10426.35	15484.77	25934.76	33028.91

The temporal scope of the analysis was set between 1995 and 2014 for multiple reasons. First, it allows to create 4 timeframes of 5-year non-overlapping interval averages to avoid a large variation of year-to-year differences in individual patent applications of regions. Second, it allows for a relatively recent picture of green technology development in Europe, while avoiding missing patent information due to time lags between the filing of a patent application and its subsequent publication. Third, a joint report by the EPO and the United Nations Environment Programme has tracked the development of European and worldwide trends in climate change mitigation technologies between 1995-2011 (EPO, 2015), which allows for concise comparison of the results. Also, EU countries have adopted a number of increasingly stringent policies for carbon emission reduction since the mid-1990s (EPO, 2015). The geographical scope of the analysis is limited to the NUTS2 regions in the EU-28, plus Iceland, Norway, and Switzerland, involving a total of 223 regions.

3.3 Measuring Green Regional Fitness & Technological Complexity

A green technology fitness ranking is developed for each timeframe. This is based on the Economic Fitness-Complexity (EFC) approach, developed by Tacchella et al. (2012), as an alternative to the Economic Complexity Index (ECI) as proposed by Hidalgo & Hausmann (2009). By coupling the economic fitness of a country or region to the complexity of a product or technology in a non-linear way, it corrects for several of the methodological shortcomings of the linear Method of Reflections (see Tacchella et al., 2012).

The EFC itself has already proven to be useful in different empirical settings, ranging from exported goods and labour sectors in bipartite country networks (Tacchella, Mazzilli & Pietronero, 2018; Sbardella, Pugliese & Pietronero, 2017), to more complex networks between patenting activity, scientific production and exported goods of countries (Pugliese et al., 2017) and has been methodically refined through simulations and performance assessments (Mariani et al., 2015).

The chosen approach follows the green-sector fitness approach, which has been proposed by Sbardella et al. (2018) for countries using the ENV-TECH patent classification (OECD, 2016). It is thus explicitly not an application over the whole technology space of an economy, but is constrained to a subset of classes, in this case, green technologies (Sbardella et al., 2018).

In a first step, all patent applications were filtered according to the geographical and temporal and technological scope as outlined in 3.1, such that the remaining patents all contain at least one green technology class. Then, the patent applications were grouped together by NUTS2 regions and green technology class for each timeframe. In the case of multiple inventors at multiple NUTS2 regions and in the case of multiple green technology classes on a single patent application, a fractional count was utilized (i.e. Rassenfosse et al., 2014).

Based on this, the regional green technology base is measured by constructing a weighted matrix $W_{r,t}$ (y) where all the fractional counts of inventions attributed to region *r* and green technology class *t* in the timeframe *y* are combined. Then, for each timeframe the weighted matrix is binarized based on the Revealed Technological Advantage (RTA), which is the Revealed Comparative Advantage (RCA) applied to patent data as proposed by Balland & Rigby (2017), to obtain $M_{r,t}$ (y), following Sbardella et al. (2018) such that:

$$M_{r,t}(y) = \begin{cases} 1, & if \ \dfrac{W_{r,t}}{\sum_{t'} W_{r,t'}} > \dfrac{\sum_{r'} W_{r',t}}{\sum_{r',t'} W_{r',t'}} \\ 0, & otherwise \end{cases}$$

Using the Balassa index (Balassa, 1965), the RTA thus reflects the intensity of the contribution of each region r to the development of green technology class t at timeframe y against the reference region r‘ ,which in this case are all the European NUTS2 regions. The binary variable assumes the value 1, when a region possesses a greater share of patent fractions in green technology class t than the reference region, and 0, when this share of patent fractions is smaller.

Two measures which can be derived directly from the matrix M are of conceptual importance in this work: the diversity d of each region r, which calculates how many green technologies a region has RTA in by summing across the rows of the matrix. And the ubiquity u of each green technology t, which calculates how many regions have RTA in that green technology by summing across the columns of the matrix. That is:

$$d_r = \sum_t M_{r,t}$$

and

$$u_t = \sum_r M_{r,t}$$

Subsequently the binary matrices M are plugged into the EFC algorithm, as described by Sbardella et al. (2018) to yield each region's green fitness score, defined by the average complexity of a region's green technologies, and each green technology's complexity score (see Appendix I for the formula). The intuition behind the EFC algorithm is that it constitutes an iterative ordering mechanism with a mean of 1 at each timeframe; it assigns higher fitness values to regions which have a higher number of green technologies that they produce with RTA (=*diversity* of r), while penalizing for green technologies that have a larger number of regions where they are produced with RTA (=*ubiquity* of t).

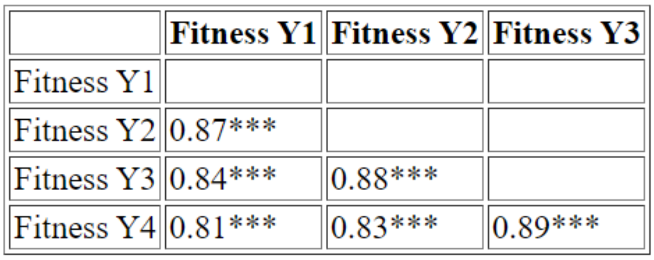
Furthermore, the EFC allows for adjustments of the extremality parameter γ, which controls the sensitivity of the penalizing effect and the number of iterations n. Following the simulations of Mariani et al. (2015), the extremality parameter γ was set to 2, with the number of iterations n=1000. Inspired by criticism of the EFC's sensitivity to rare occurrences, green technology main groups with ubiquity $u < 4$ and regions with diversity $d < 4$ were excluded at each timeframe (Morrison et al., 2017). Overall, this has smoothed the convergence properties of the EFC calculations. Table 4 provides an overview of the number of included green technology main groups and regions at each timeframe.

Table 2: Number of regions and green technologies

Period	Tech Groups	Regions
1995-1999 (Y1)	138	170
2000-2004 (Y2)	160	186
2005-2009 (Y3)	179	214
2010-2014 (Y4)	181	223

While it seems to be methodologically impossible to properly distinguish mere technological rarity from technological complexity by solely relying on such a data-driven method without further expert evaluation, the resulting rankings seem fairly robust and sufficiently stable across time. Table 3 provides the Spearman-Rank Correlation of the regional fitness ranks between the timeframes. Table 4 provides the Spearman-Rank Correlation of the technological complexity between the timeframes. For regions, the correlation is very strong, while for technologies it is moderate to strong; this is in line with the higher heterogeneity of green technologies observed by Sbardella et al. (2018). Importantly, for regions, it seems that changes in the regional fitness rankings were not driven by additions of only very complex or rare technologies. All the mentioned steps were operationalized using the implemented functions in the R package economiccomplexity (Vargas, 2020).

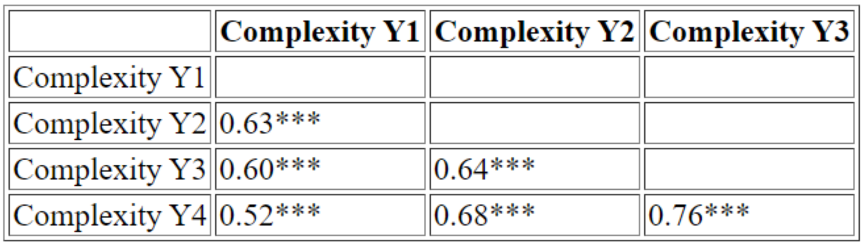
Table 3: Correlation of Regional Fitness between timeframes



	Fitness Y1	**Fitness Y2**	**Fitness Y3**
Fitness Y1			
Fitness Y2	0.87***		
Fitness Y3	0.84***	0.88***	
Fitness Y4	0.81***	0.83***	0.89***

****p<0.01; ** p<0.05; *p<0.1.*

Table 4: Correlation of Technological Complexity between timeframes



	Complexity Y1	Complexity Y2	Complexity Y3
Complexity Y1			
Complexity Y2	0.63***		
Complexity Y3	0.60***	0.64***	
Complexity Y4	0.52***	0.68***	0.76***

***p<0.01; ** p<0.05; *p<0.1.

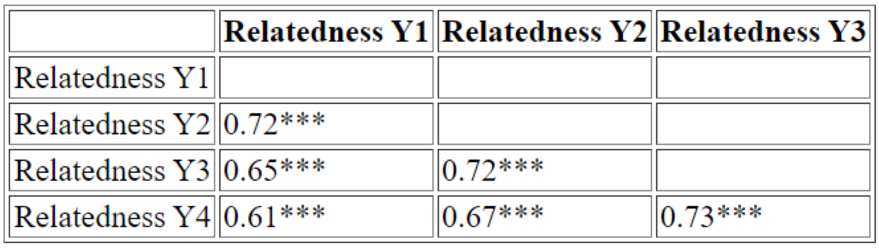
3.4 Measuring Green Technological Relatedness & Relatedness Density

The green technological relatedness concept was operationalized following Boschma et al. (2015), as the spatial co-occurrence of technologies, such that the more often technologies are co-produced in the same regions, the more related they are. Essentially building on the product space idea developed by Hidalgo et al. (2007) and their product proximity measure, relatedness φ between all technologies i and j is computed by taking the minimum of the pair-wise conditional probabilities of a region patenting in class i with RTA, given that they patent in class j with RTA during the same time period, such that:

$$\varphi_{i,j,y} = min\big(P\big(RTA_{i,t} > 1 \big| \, RTA_{j,t} > 1\big)\, , P\big(RTA_{j,t} > 1 \big| \, RTA_{i,t} > 1\big)\big)$$

In the context of green complexity studies, this measure was also used by Mealy & Teytelboym (2020) to derive future green product diversification opportunities. However, their relatedness measure is exclusively based on the subset of green products, which might disregard potential non-green capabilities that could however still influence green capabilities in the cases of similar knowledge bases. To deal with this shortcoming, the relatedness for each technology class pair was calculated using the entire European technology space. Inspired by van den Berge et al. (2019), all the non-green technologies were aggregated at the sub-class level (e.g. C10J), while the green technologies remained at the main group level. For reasons of consistency at each timeframe y, only the green technology main groups t and the European regions r which were included in the fitness-complexity calculations were used (see Table 2). Furthermore, to avoid computation issues with very small classes, a threshold of 30 patents for the non-green technology classes at each timeframe was introduced similar to Balland et al. (2019). Overall, this was seen as a sensible approach to sufficiently capture the relatedness of green technologies in the European technology space, while providing a relatively stable measure over time, as shown by the strong correlation of relatedness between timeframes in Table 5, which is consistent with the empirical patterns of regional path-dependence regarding technological relatedness (see e.g. Boschma et al., 2015).

Table 5: Correlation of Relatedness between timeframes



	Relatedness Y1	Relatedness Y2	Relatedness Y3
Relatedness Y1			
Relatedness Y2	0.72***		
Relatedness Y3	0.65***	0.72***	
Relatedness Y4	0.61***	0.67***	0.73***

****p<0.01; ** p<0.05; *p<0.1.*

Based on this, the relatedness density was calculated as in Boschma et al. (2015), such that:

$$Relatedness\ Density_{i,r,y} = \frac{\sum_{j\in r, j\neq i}\ \varphi_{i,j}}{\sum_{j\neq i}\ \varphi_{i,j}} * 100$$

The relatedness density provides a relative measure of how related any given technology i is to the existing knowledge structure of any region r. It takes the technological relatedness $\varphi_{i,j,y}$ of technology i to all other technologies j in which a region r has RTA, and divides it by the sum of technological relatedness of technology i to all other technologies j in the European reference space. Higher density indicates a closer technological relatedness of a given technology towards the existing set of technologies in the region. In this work, the measure is used in two ways: first, to calculate how related green technologies are in any given region, by taking the average relatedness density of a) all green technologies that are produced in the region with RTA and/or b) all green technologies that are not produced in the region with RTA and are thus absent from the technology portfolio. Based on the general pattern of related diversification of regions, this provides an indication of how likely a region is to further diversify into both more and more complex green technologies (Balland et al., 2019). The second use is to evaluate the relatedness of the entry-exit-remain dynamics, where relatedness is understood rather as a matter of degree than in a dichotomous way. This is done by subtracting the mean of all newly added, exited and remaining green technologies between two timeframes from each of those green technologies (which are either added, exited, or remain) and dividing by the standard deviation of this variation.

3.5 Measuring the Green Technology Life Cycle

The green technology life cycle stages were calculated following Barbieri et al. (2020) by combining the information on the ubiquity *u* of each green technology with the patenting intensity of each green technology. The green technology life cycle is thus a relative measure within the green technology space and allows to distinguish between green technologies that are relatively more developed against those that are relatively less developed. The ubiquity *u* is again derived based on the RTA, while patenting intensity is simply based on the total volume of patenting as captured by the fractional patent count for each green technology group.

As suggested by Barbieri et al. (2020), this allows to distinguish between 4 life cycle stages as shown in Table 6: emergence, development, diffusion, and maturity. Emergence technologies are characterized by patenting intensity and ubiquity below average. Development technologies have an above-average patenting intensity but maintain a below-average ubiquity. Diffusion technologies are above average in both patenting intensity and ubiquity, while for maturity technologies, the ubiquity is above average, and patenting is below the average of all the green technologies. To calculate this, the full set of green technology main groups *t* was used, and the ubiquity calculated based on all European regions *r* at each timeframe *y*.

Table 6: Green Technology Life Cycle Stages

	Ubiquity		
Patenting Intensity		Lower than Ø	Higher than Ø
	Higher than Ø	**Development**	**Maturity**
	Lower than Ø	**Emergence**	**Diffusion**

As the number of included green technology groups increases substantially and to at least observe how those novel technologies affect the regional fitness, related to the methodological concern of rare occurrences being the dominant driver of ranking changes as discussed in 3.3, a further “pre-emergence” stage was considered in the green life cycle stage, as new-to-the-world technologies. These are defined as those green technologies that have not received a complexity score in the timeframe *y* but receive a complexity score in subsequent timeframe *y+1*. This was seen as a pragmatic approach as these technologies are treated as newly entering the green technology space.

3.6 Regional Innovation Capacity

As a regional dimension, previously developed innovation typologies of European regions (OECD, 2011b; Wintjes & Hollanders, 2010) as well as the Regional Innovation Scoreboard of 2014 (European Commission, 2014) are utilized. Thus, each European region is assigned their respective innovation typology. This is done to 1) contextualize the fitness ranking and identify the respective leaders and catch-up regions for each typology, to 2) select as diverse set of regions as possible to allow for potential diversity of regional green growth diversification pathways and to 3) contextualize the observed diversification pathways according to the regional innovation capacity. While the Innovation Scoreboard and the typology by Wintjes & Hollanders (2010) was used to triangulate the results, the qualitative understanding of the regional innovation capacity was derived from the OECD (2011b). Table 7 provides an overview of those regional categories.

Table 7: Summary of Regional Innovation Capacity

Regional Typology (Cluster)	**Main Characteristics**	**Label**	**N**
Knowledge Hubs			
Knowledge-intensive city/capital districts (i.e. Brussels, Vienna, Hamburg, London)	*Densely populated capital or city districts with high R&D and patenting intensity* • High share of services in knowledge-intensive sectors • Highly educated workforce • Small geographic size and commuting results in on average very high GDP per capita • Relatively high unemployment rate	Capital	7
Knowledge and technology hubs (i.e. Île-de-France, Middle Franconia, South East England, Stockholm)	*Top knowledge and technology regions* • By far highest average levels of R&D and patenting intensity • Highest average share of R&D conducted by business • Significant share of manufacturing in high-technology sectors	Hub	30
Industrial Production Zones			
Service and natural resource regions in knowledge-intensive countries (i.e. Central Jutland, Utrecht, Scotland, Bratislava Region)	*Second-tier regions in knowledge-intensive countries* • Smaller geographic scale and/or less densely populated • Highly educated workforce • High share of employment in knowledge-intensive sectors or natural resources • Limited manufacturing in sectors of lower technology level than other Industrial Production Zones	Service	28
Medium-tech manufacturing and service providers (i.e. Brittany, Basque Country, Arnsberg, Central Hungary)	*Industrial production regions and some capital regions of middle-income countries* • Strong medium-low and medium-high-technology industrial base • Relatively high knowledge absorptive capacities • Significant share of labour force with tertiary education	Medium-Tech	55
Traditional manufacturing regions	*Regions specialized in traditional medium-low and low-technology sectors*	Traditional	29

(i.e. Lower Austria, Lombardy, Central Bohemia, Lazio)	• Highest share of employment in manufacturing • Relatively lower-skilled labour force • Average R&D investments and patenting • Medium-low GDP per capita		
Non-S&T-Driven Regions			
Structural inertia or deindustrialising regions (i.e. Brandenburg, Valencia, Silesia, Calabria)	*Regions with persistent “underdevelopment” traps* • Face a process of de-industrialisation or experience structural inertia • Considerably lower GDP per capita • Highest average unemployment rate • Values on S&T-related indicators are low	Inertia	34
Primary-sector-intensive regions (i.e. Masovia, Lesser Poland, Central Macedonia, Southern Great Plain)	*Southern and Eastern European regions with low population density* • Significant share of economy in primary sector activities or low-technology manufacturing • On average lowest values on S&T-related indicators	Primary	28

Table 8 provides a summary of the operationalization and measuring of the different dimensions.

Table 8: Operationalization Table

Concept	Dimensions	Indicators	Calculation of Scores
Complexity of Green Capabilities	Economic Complexity	Green Regional Fitness (Sbardella et al., 2018)	Rank per region
	Technological Complexity	Green Technological Complexity (Sbardella et al., 2018)	Rank per green technology
Relatedness of Green Capabilities	Technology to Technology	Technological Relatedness (Boschma et al., 2015)	Pairwise score between 0 and 1 for all technologies
	Technology to Region	Green Relatedness Density (Boschma et al., 2015)	Ø Relatedness Density to green technologies per region with a) Green RTA = 1 b) Green RTA = 0
	Technology Dynamics to Region	Green Dynamics Relatedness Density	Standardized Relatedness Density per (exited, entered, remaining) green technology in a region
Green Technology Life Cycle	Stages of the TLC	Ubiquity (Barbieri et al. 2020)	Number of Regions with RTA per technology
		Patenting Intensity (Barbieri et al., 2020)	Fractional Patent Application Count per technology
Regional Innovation Capacity	Regional Typology	Categorisation of OECD Regions using Innovation-related Variables (OECD, 2011)	Category Label

3.7 Analysing Contextual Green Growth Diversification Pathways

To answer the first research question, which European regions have successfully diversified into more complex green technological capabilities over time, the green technology fitness ranking is analysed by observing the ranking changes between each regions' initial and the last timeframe, similar to the country-level studies conducted Mealy & Teytelboym (2020) and Sbardella et al. (2018). With the increase of green patenting output and its spatial ubiquity, diversification into more complex green technological capabilities can be observed relatively between the regions, as the fitness ranking directly depends on the complexity of the green technology portfolio. Observing the ranking changes then provides an intuitive way of comparing the relative regional performances across time. Based on the ranking spot at Y1 and Y4, as well as the rank change between Y1 and Y4, the green fitness leaders and catch-up regions are identified; acknowledging that differences in the regional innovation capacity certainly influences which regions are at the top or bottom of the ranking, the leading and catch-up regions are defined as those within the top 10% of their respective innovation typology (i.e. Hub, Medium-Tech, Inertia etc.) in terms of ranking spots and ranking spot improvements. This allows 1) to account for the regional dimension in studying potential pathways and allow for more diversity, 2) to provide a group-wise benchmark also for regions that would generally not be very likely to outperform other regions, for instance Inertia regions as compared to Hub regions and to 3) explain possible catch-up behaviour either in terms of or despite a lack of general regional innovation capacity and to 4) to only study the very successful leaders and catch-up regions. To triangulate the results, the identified regions are compared across the different typologies and only those regions that belonged to the leading group or catch-up group in at least two of those typologies are kept.

To answer the second research question, what the similarities and differences between catch-up regions with regards to their green growth diversification pathways are, a set of three catch-up regions from different innovation typologies are selected. For these regions, the European technology space was constructed for each timeframe, by using the information on the technological relatedness. Each technology represents a node, and is connected via edges, fulfilling two conditions: 1) each node is connected to its most related node, i.e. each technology is connected to the technology with its maximum relatedness; 2) edges between nodes were added until the average degree of linkages in the network was 5, to limit the amount of connected nodes to only fairly related ones, while allowing to still visually explore the dynamics over time. This was done by using the R package economiccomplexity (Vargas, 2020). The visualization of the network uses the Kamada-Kawai force-directed algorithm, as implemented in the

R package ggraph (Pedersen, 2017).

Based on this, in each technology space, the technological dynamics between two timeframes are visualized, by colour-coding the green technologies according to remaining, newly added and exited green technologies, setting the node sizes according to the complexity quartile and labelling the nodes according to their green technology group. This allows to identify diversification pathways for each region by exploring questions such as where in the technology space which changes happen, whether technology clusters can be observed or whether some technologies occur as isolates, and whether this is different for different levels of complexity.

To facilitate this exploration, a second figure is provided for each timeframe, which maps all the green technologies that remain, are exited or entered within the region according to their complexity at the timeframe of the technology space (which itself is based on the technological relatedness within all of Europe at that timeframe) and according to its relatedness density (which relates the technological relatedness to the regional portfolio) at the prior timeframe. This time difference allows to study the effect of relatedness in subsequent diversification for technologies, that are not yet part of the regional technology portfolio. Furthermore, this coupled approach allows to use both the information provided by the relatedness representation in the European technology space, as well as the relatedness density within the region. This is interesting for cases, where i.e. a region is competitive in a technology at the periphery of the technology space, while it has the vast majority of all other RTAs at the opposite end of the technology space. Then, an entry into an adjacent technology close to the isolate at the periphery might be considered as unrelated if measured by the regional relatedness density; but if observed by the relatedness within the technology space, where both those technologies are connected, they might be considered as related. This is in line with the earlier suggestion, that this explorative account can help to account for nuances regarding the studied concepts. In addition, to account for differences across the green technology life cycle, the life cycle stages of all newly entered technologies are highlighted in the second figure.

Using this approach an in-depth account of the technological dynamics and diversification pathways for the different regions over time is provided. In particular, the role of relatedness in the different catch-up regions with differing innovation capacity, for different degrees of technological complexity and across the technological life cycle is critically reflected.

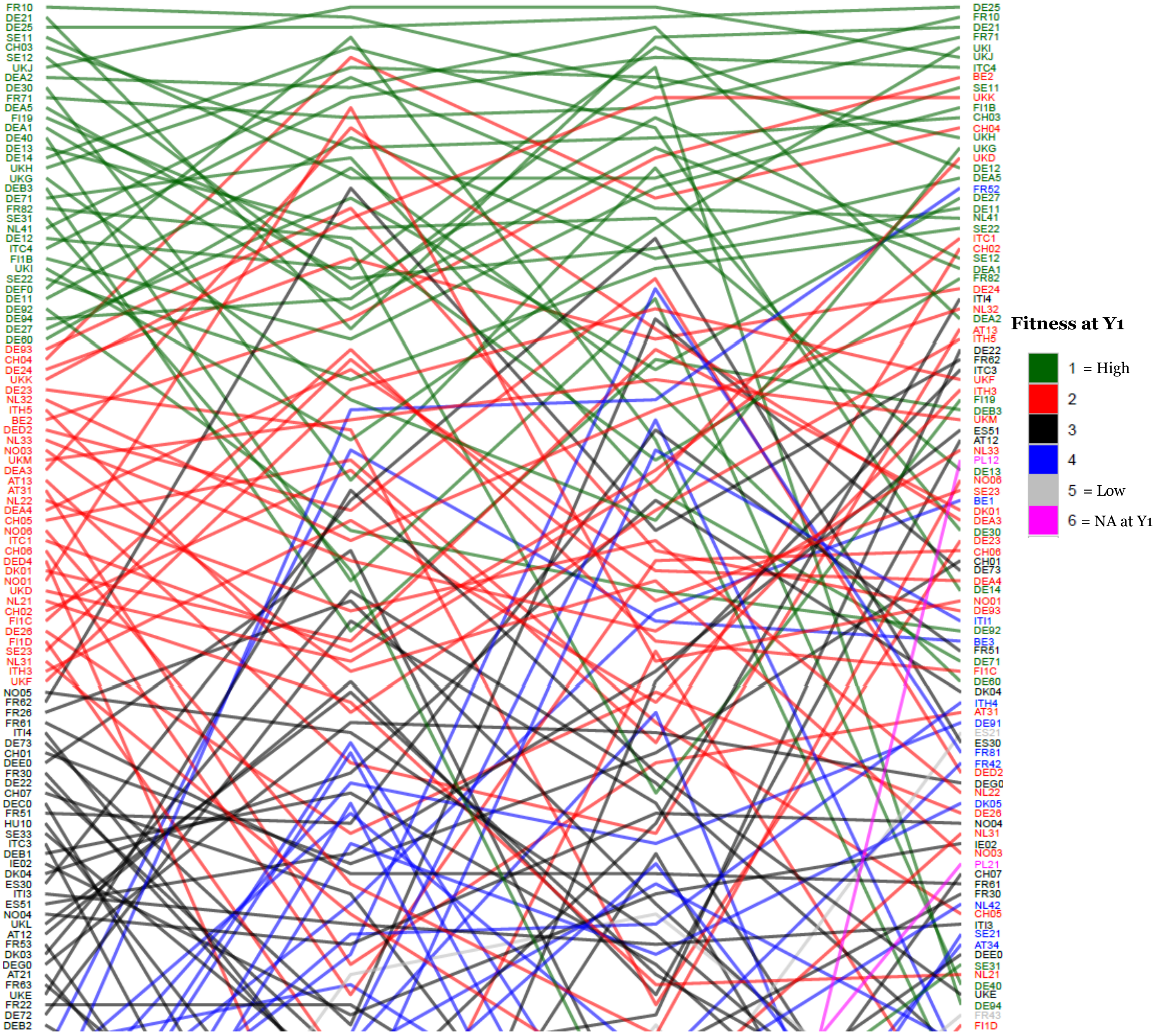
4 Results

4.1 Green Growth – An Overview

The European green technology fitness ranking is utilized to identify which European regions have successfully diversified into more complex green technological capabilities over time, consistent with the notion of green growth. To do so, Figure 2 provides an overview of the fitness ranking evolution, in which regions are color-coded according to their starting quintile in the first timeframe *y*=1 (1995-1999). For regions at the lower end, see Appendix II.

4.1.1 Green Technology Fitness of European Regions

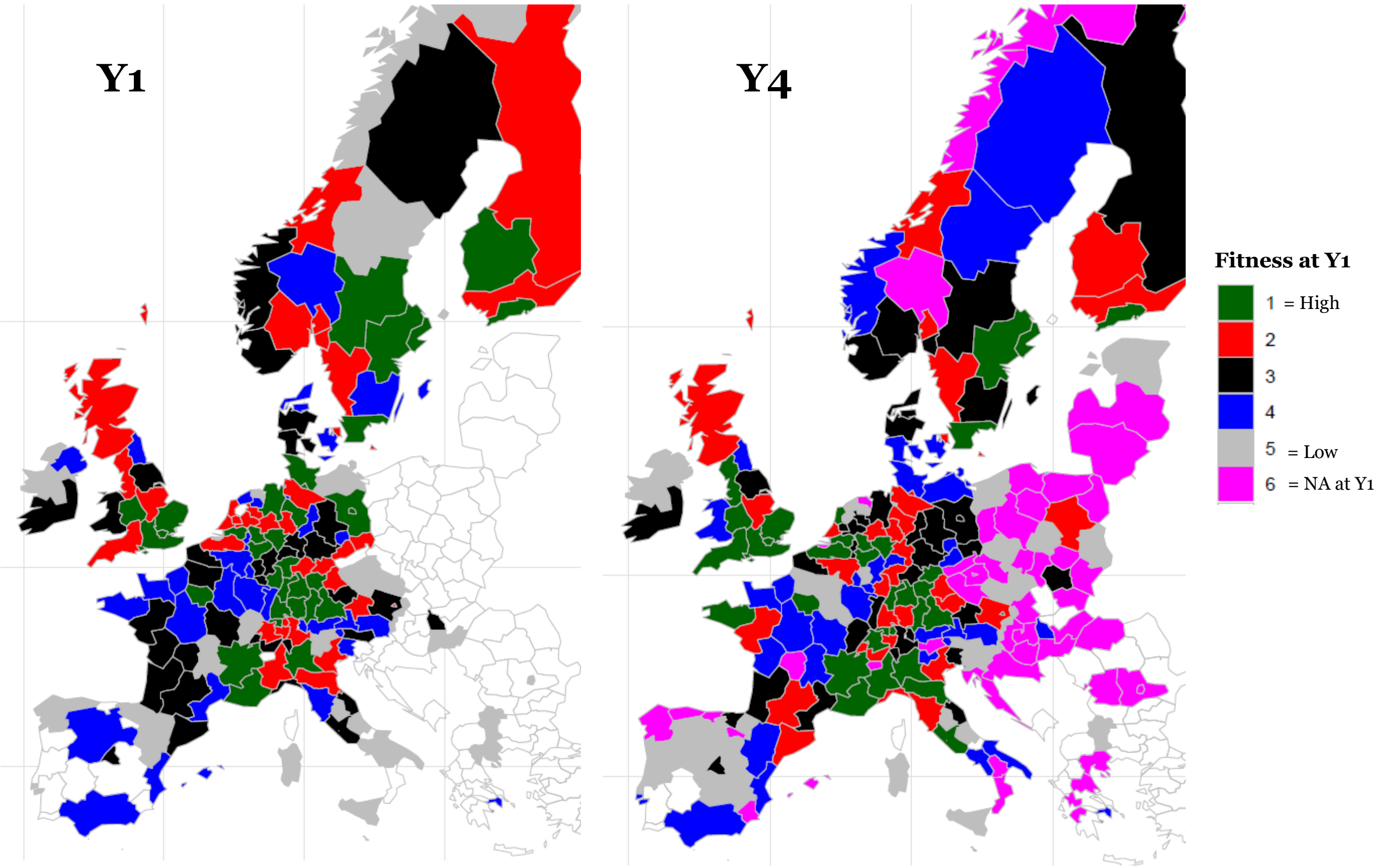
Figure 2: Green Technology Fitness Evolution of European Regions



As can be observed in the ranking, European regions at the top of the ranking are relatively stable over time; most notably, Île-de France (FR10), Upper Bavaria (DE21) and Middle Franconia (DE25) are among the top 3 regions in both the first timeframe and the last timeframe. Nonetheless, some former top regions, such as North Middle Sweden (SE31), Brandenburg (DE40) and Weser-Ems (DE94) have dropped considerably in the ranking. Contrary to those, several regions managed to climb the ranking and join the top group, most notably Brittany (FR52) and Lazio (ITI4). Furthermore, the newcomer regions Masovia (PL12) and Lesser Poland (PL21) seem to have been particularly successful in developing more complex green capabilities over time, similar to Brussels (BE1) and Basque Country (ES21). Overall, the observed changes over time seem to be fairly gradual, with the majority of regions either staying in their group or dropping or climbing towards an adjacent group.

These initial observations confirm 1) the stickiness of more complex green capabilities also at the regional level, consistent with the observations at the national level (Mealy & Teytelboym, 2020; Sbardella et al., 2018) and 2) the existence of catch-up regions that have done particularly well in improving their ranking spots relative to all other European regions.

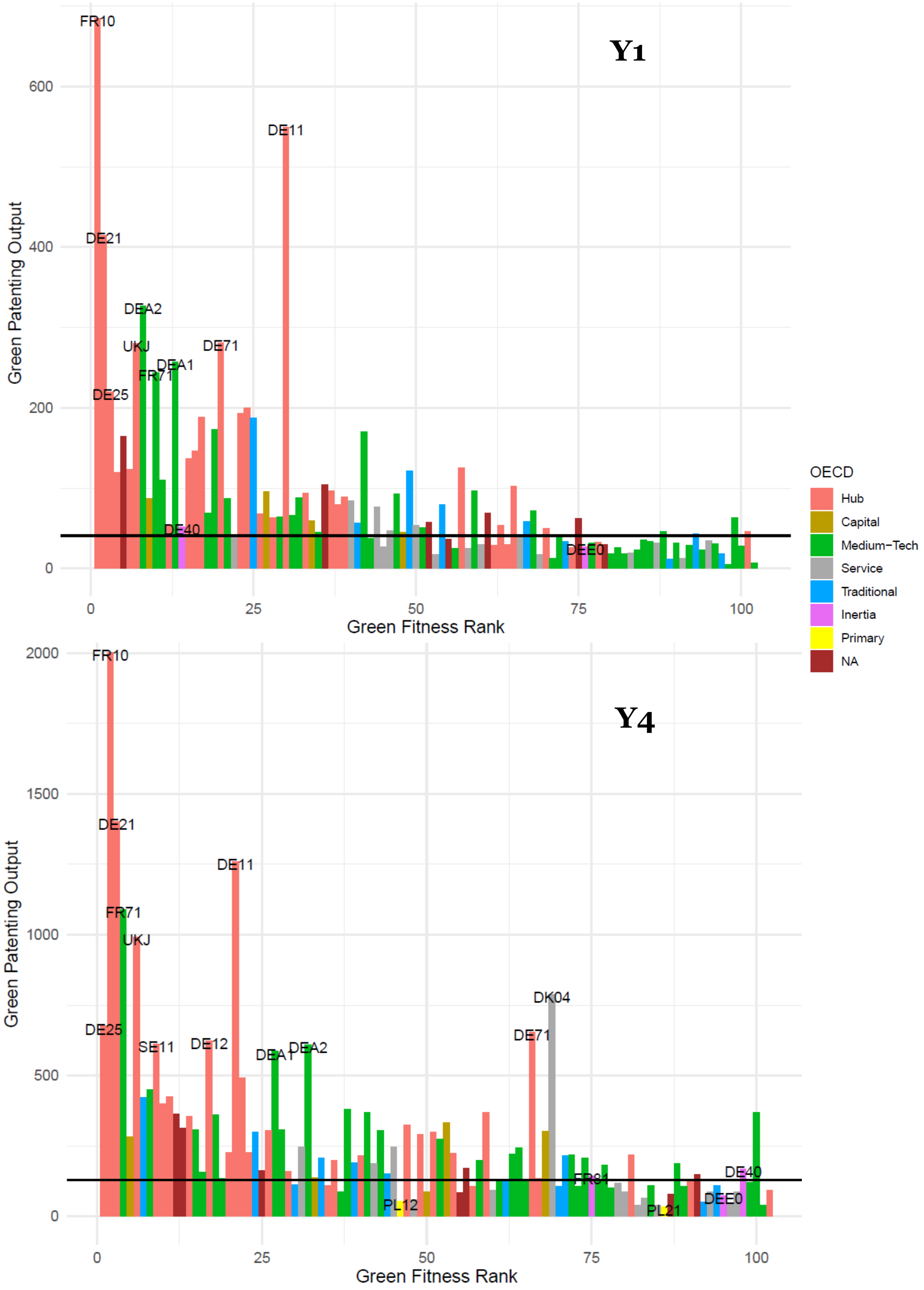
Figure 3: Green Technology Fitness Maps at Y1 and Y4



To provide more context to the ranking evolution, the geographical distribution of the ranking is shown in Figure 3. Consistent with the generally observed patterns of a core-periphery divide in regional economic studies (see e.g. Marques & Morgan, 2018), the top green fitness regions are mainly clustered in the Southern and North-Western part of Germany, in the South of the UK, Southern Sweden and Finland and in Southern France; on the other hand, the low green fitness regions can be mainly found in Spain, the South of Italy and generally in the South-East of Europe. While some of these regions manage to develop some green technological capabilities over time, they mostly stay among the least fit regions. At the top of the ranking, the regions adjacent to and clustered around the Mediterranean Sea (Southern France, North-Western Italy, and North-Eastern Spain), seem to have done particularly well in climbing the ranking by at least one group, whereas some North-Eastern German regions have dropped by several groups. Nonetheless, the relative stability of the ranking also holds true geographically.

To further contextualize the ranking beyond the geographical dimension, the regions' general innovation capacity is considered, alongside their green patenting output in Figure 4. Similar to the general patenting output, green patenting output is skewed, with a few regions with very high patenting intensity, such as Île-de France (FR10), Upper Bavaria (DE21) and Stuttgart (DE11). Higher green patenting output seems to be fairly in line with higher green complexity; nonetheless, some regions have considerably lower patenting intensities and still manage to be among the top, in line with the finding by Balland & Rigby (2017), that cities with the most complex technological structures are not necessarily those with the highest patenting rates. Conversely, regions such as Central Judland (DK04) and Darmstadt (DE71) have fairly high green patenting output but seem to focus their patenting endeavours on comparatively lesser complex technologies. Accounting for the general innovation capacity of regions, the top 25 ranking spots are mostly dominated by Hub and Medium-Tech regions in both timeframes; while nearly all of the Hub regions are among the top 100, the Capital, Medium-Tech and Service Regions have around 56-70% of their respective regions in the top 100. On the other hand, of the Traditional Manufacturing Regions, 37% are among the top 100, while Inertia and Primary regions are rather the exception. This might also explain why for instance Brandenburg (DE40) and Saxony-Anhalt (DEE0) have dropped in the ranking, once other, more endowed regions have diversified into more green technologies. Opposing this trend, Masovia

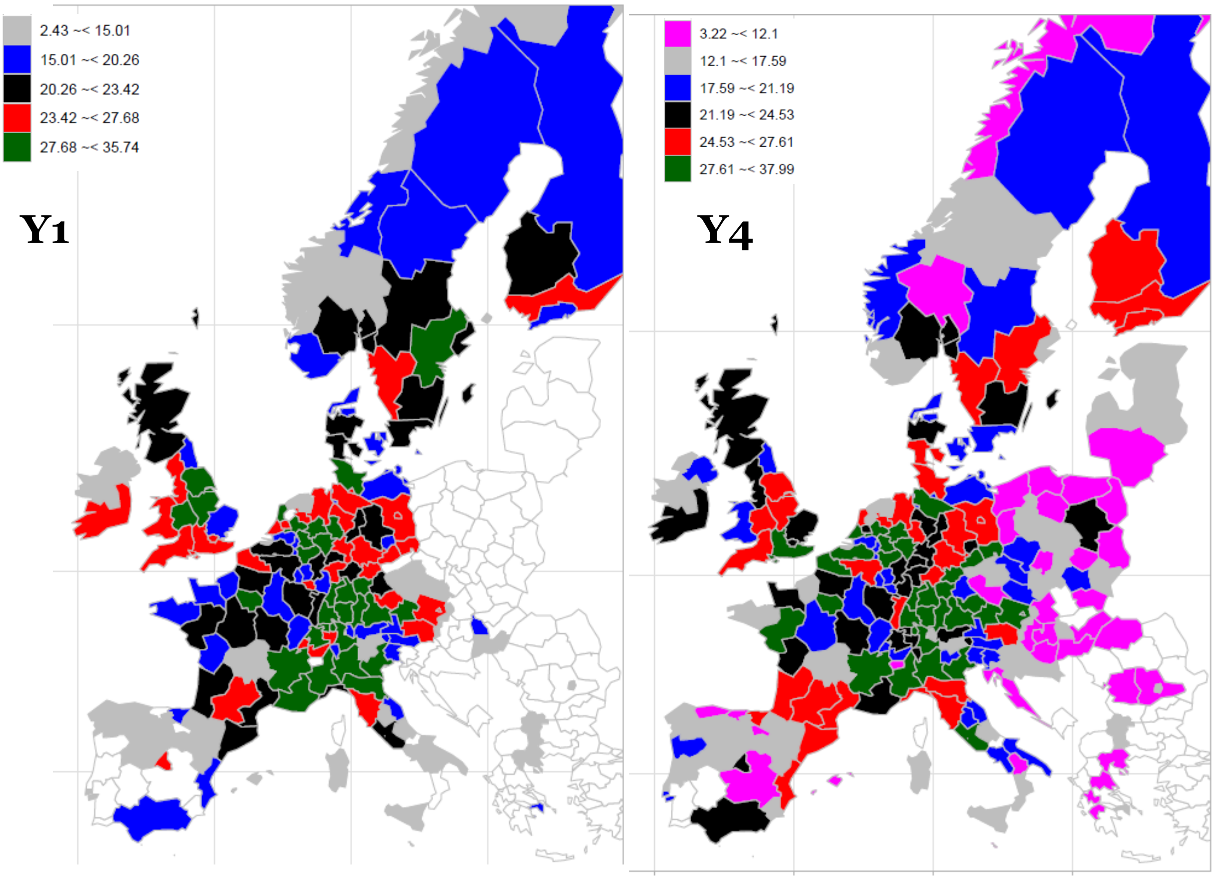
Figure 4: Green Fitness & Green Patenting Output at timeframes Y1 and Y4



(PL12), Languedoc-Roussillon (FR81) and Lesser Poland (PL21) have surpassed some of those regions. Overall, despite some variation, this suggests that the general innovation capacity of regions is a considerable factor also for green growth opportunities and should be further considered in understanding possible diversification pathways.

In studies which consider technological complexity in assessing future diversification opportunities, it is a standard practice to provide an account of the relatedness density of all the technologies that are not part of the regional technology portfolio (RTA = 0) (see i.e. Balland et al., 2019). This is due to the established account in EEG, that regions with higher relatedness density are more likely to diversify in more and more complex technologies in the future (Balland et al., 2019). Therefore, Figure 5 provides an overview of the average relatedness density of the green technologies that are not part of the regional technology portfolio at Y1 and Y4, respectively.

Figure 5: Green Average Relatedness Density Maps at timeframe Y1 and Y4



By and large, the maps look fairly similar to the fitness maps at the respective timeframes. Regions with high relatedness density are clustered in the Southern and North-Western part of Germany and most notably, the cluster around the

Mediterranean in the North of Italy and South of France is already visible through the high relatedness density in the first timeframe. Also, for some of the Northern and Eastern German, as well as Swedish and Finnish regions that have eventually lost their position in the complexity ranking, the low green technology relatedness seems predictive of this eventual decline. This confirms the general relationship between average relatedness density and future more complex diversification. If this continues to hold, judging by the relatedness density map at the last timeframe, a further decline in terms of green complexity might be expected for Scandinavia, and the UK, while German regions might be expected to fare better again. Furthermore, the general core-periphery divide, especially for Eastern Europe might remain.

In contrast to this, some individual regions seem to have managed to successfully deviate from this general pattern of higher relatedness density leading to a higher complexity and vice versa at different points in time. For instance, North Brabant (NL41), Helsinki-Uusimaa (FI1B), and Stockholm (SE11) are at the top of the fitness ranking in both the first and last timeframe; while North Brabant remains in the fourth relatedness density quintile throughout and only increases its average relatedness density from 15.7 to 18.4, the missing green technologies in the technology portfolio of Helsinki-Uusimaa become much more related, increasing from 19.88 to 24.67; consequently, Helsinki-Uusimaa is ranked in the second relatedness quintile in the last timeframe. The opposite is true for Stockholm: despite experiencing a decline in its average relatedness density from 21.68 to 16.83 and dropping from the third to the fifth relatedness quintile, the region still manages to remain in the top fitness group.

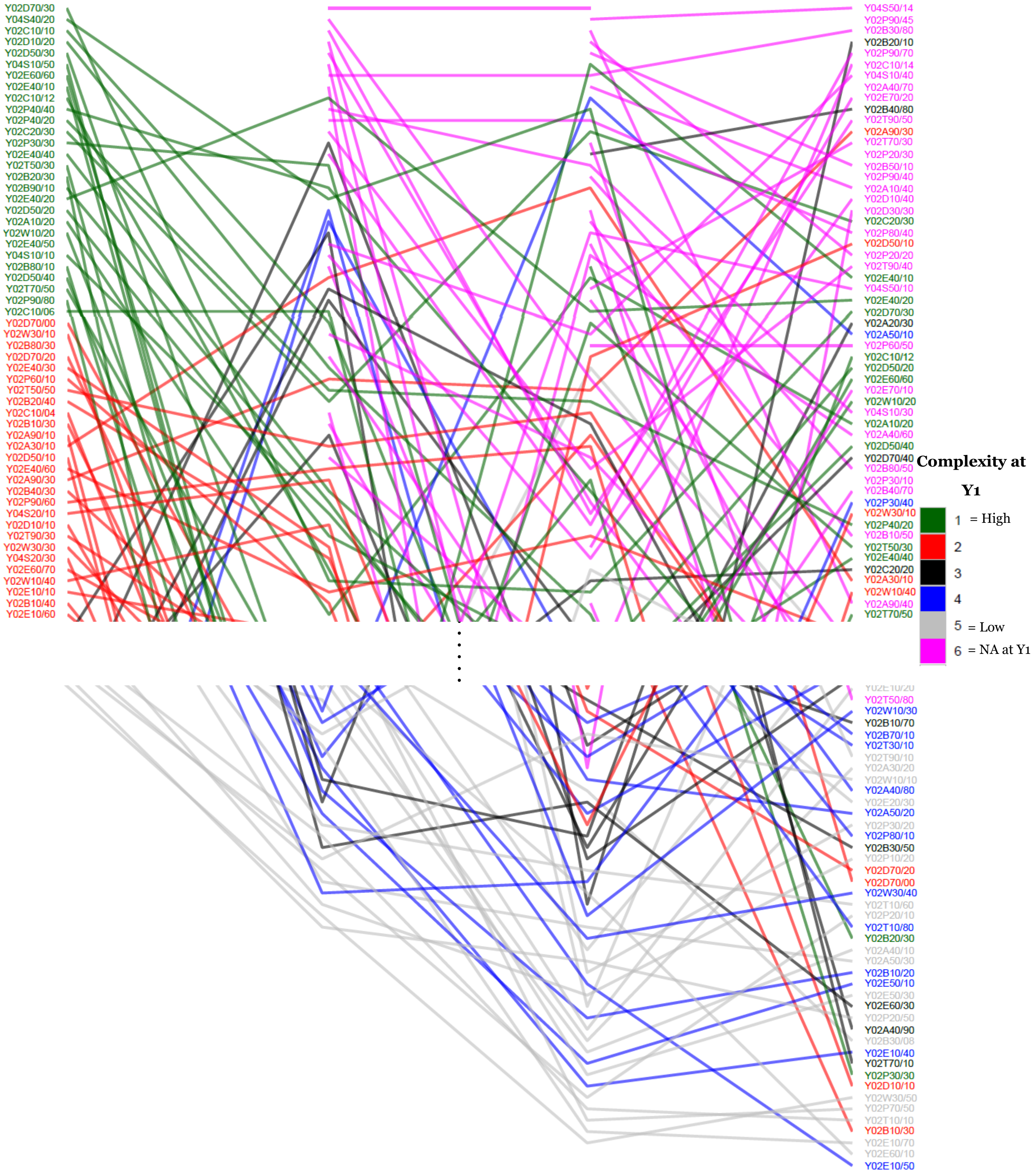
Summary

While the general patterns of path-dependence and regional economic development seem to be also true for green technology development, in line with earlier work (Santoalha & Boschma, 2019; van den Berge et al., 2019; Montresor & Quatraro, 2019; van den Berge & Weterings, 2014), the variety that could be observed in the evolution of individual regions, that is 1) the existence of green complexity catch-up regions in Europe, 2) the ability of some regions to outperform other regions in terms of the complexity of their green portfolio, despite lower patenting rates and despite a lower general innovation capacity and 3) the finding that relatedness density seems to be of differing importance for future green technological complexity in some regions justifies the need to explore the diversity of green growth diversification pathways along regional and technological dimensions, as is proposed in this work.

4.1.2 Green Technological Complexity

After this regional overview, the technology dimension is considered. Figure 6 provides an overview of the complexity ranking evolution, in which technologies are color-coded according to their starting quintile in the first timeframe y=1 (1995-1999). For mid-complexity technologies see Appendix III.

Figure 6: Green Technological Complexity Evolution

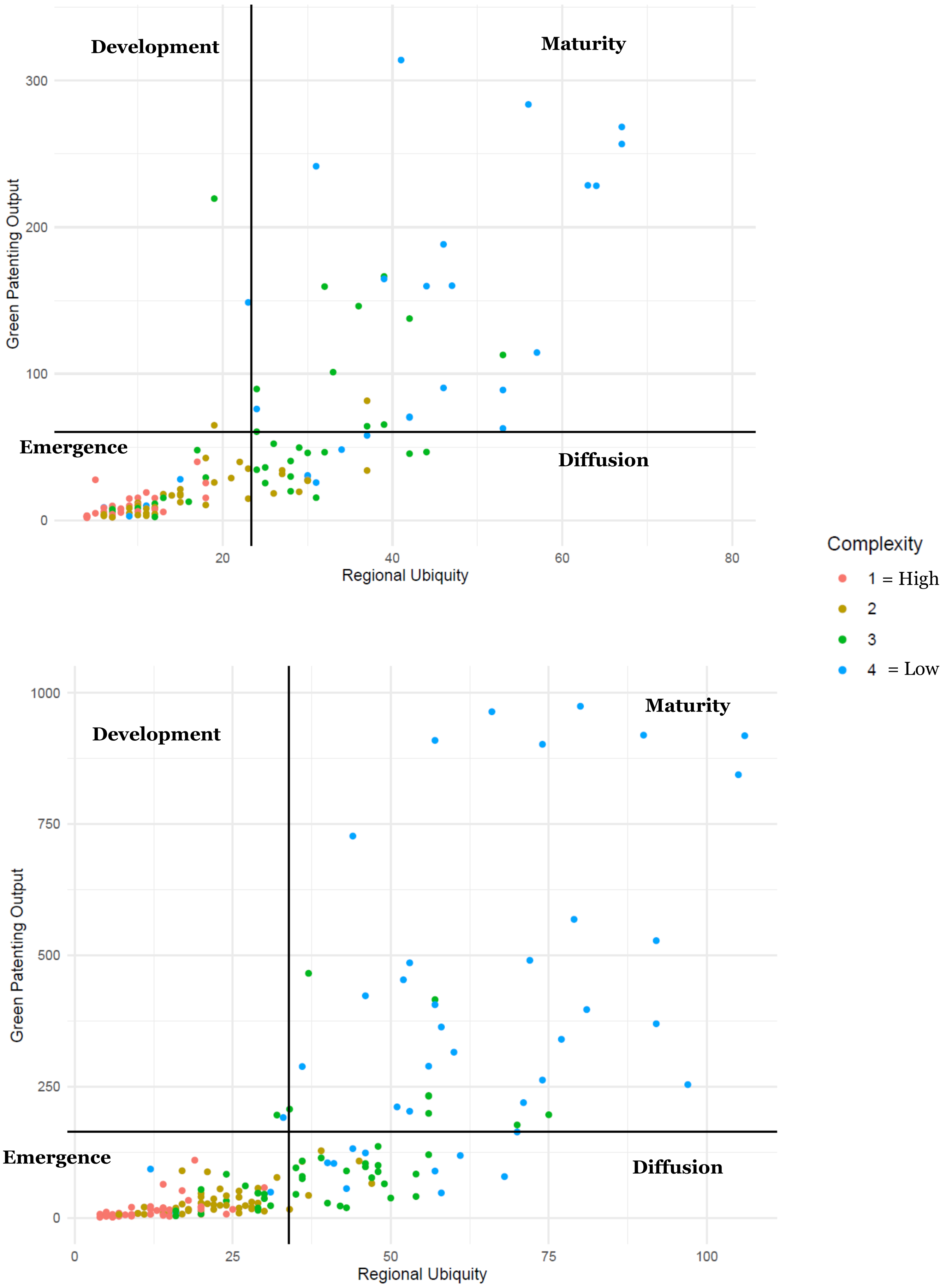


Compared to the regional ranking in Figure 2, the technological complexity ranking is much more volatile, especially at the top of the complexity ranking. In the last timeframe, the most complex technologies are mainly also novel technologies, whereas the second quintile partly consists of novel technologies and partly of the most complex technologies from the first timeframe. The three green technologies that are at the top in both the first and the last timeframe are "Capture or disposal of perfluorocarbons [PFC], hydrofluorocarbons [HFC] or sulphur hexafluoride [SF6]" (Y02C20/30), "Flexible AC transmission systems [FACTS]" (Y02E40/10) and "Active power filtering [APF]" (Y02E40/20). At the low-end of the ranking, the time evolution is more stable; accordingly, the least complex green technologies at the last timeframe are "Photovoltaic [PV] energy" (Y02E10/50), "Energy storage" (Y02E60/10), and "Wind energy" (Y02E10/70), fairly consistent with the increased adoption and diffusion of those technologies (EPO, 2015).

Furthermore, no green technology class, such as the Systems Integrating Technologies, i.e. Smart Grids (Y04S) seems to be inherently more complex than others. While the high volatility could point towards problems with the measure at the comparatively detailed level of the analysis, this volatility could also be reflective of the high technological heterogeneity regarding green technologies; in line with this, Sbardella et al. (2018) also report a higher variation of the green technology ranking at their more aggregated level of observation.

As a contextual dimension to the green technology complexity ranking, Figure 7 provides an overview of the Green Technology Life Cycle stages in the first and the last timeframe. While there is considerable growth in average patenting output per green technology group from around 60 to 164, the Average Regional Ubiquity of green technologies has also increased from around 23 to 34. The vast majority of green technologies is in the Emergence stage, with 74 and 102 technologies respectively in the first and last timeframe. These emergent technologies are also generally considered more complex; in fact, the top quartile of the complex technologies in both timeframes are found among the emergent technologies, consistent with what could be observed for novel technologies in the ranking evolution. Nonetheless, 14 of the emergent technologies in the first and 29 in the last timeframe are in the lower half of the complexity ranking, with the least complex in the first being "Adaptation Technologies at coastal zones; Hard structures" (Y02A10/11), "Production or processing related to oil refining/ petrochemical industry; Bio-feedstock" (Y02P30/20) and two building-

Figure 7: Green Technology Life Cycle at timeframes Y1 and Y4



related energy-efficiency technologies (Y02B40/10; Y02B30/90). This suggests that the fitness-complexity algorithm successfully penalizes technologies if they are produced with RTA in low-fit regions and thus provides some confidence in the measure; for instance, the “Hard structures adaptation technology” is produced in East Middle Sweden (SE12) and Darmstadt (DE71) with fitness ranks 6 and 20, but also by Sicily (ITG1) and Sardinia (ITG2) with fitness ranks 158 and 165. Despite its low ubiquity (11 regions) and low patenting output (10), this results in a low-complexity score.

While Barbieri et al. (2020) describe the Development stage and Diffusion stage as alternative pathways towards technological maturity, only relatively few green technologies have a high output paired with a below-average ubiquity. Only three technologies are in the Development stage at both timeframes, with “Nuclear fission reactors” (Y02E30/30) being found in both with an output of around 200 and ubiquity just below the average. In contrast, the diffusion phase contains 27 and 37 green technologies, respectively with a fairly balanced distribution of complexity between the second and fourth quartile. Interestingly, the most complex technologies in the Diffusion stage seem to consist of more general-purpose technologies, such as enabling technologies (Y02E60/70; Y02B70/30; Y02B70/30) and systems integrating technologies (Y04S20/20; Y04S40/10). This could suggest that, on the one hand regions purposefully enter those technologies, as they are generally regarded to provide inputs for a variety of innovations due to their horizontal and systemic nature and allow for increased abilities in creating more sustainable innovation paths, link industries and create new potentials for diversifying into new sectors (see Wanzenböck, Neuländtner & Scherngell (2019) for an overview of the role of Key-Enabling Technologies (KET)). In line with this, the European Commission highlights sustainable development, energy-efficient buildings, and sustainable process industries as important pillars of KETs, in particular for the Advanced Manufacturing and Processing (European Commission, 2020). On the other hand, it also suggests that successfully innovating in those areas is difficult, as observed by the lower-than average patenting output. This finding calls for special attention to those technologies in individual regions, as they might influence the available pathways regarding green growth diversification more decisively than more targeted green technologies.

The maturity phase is fairly stable across time. Of the 34 mature technologies at the first timeframe, 28 remain within that life cycle stage with comparatively low complexity overall. Among the top 3 green technologies with the highest patenting output (>680) in the first timeframe are “Mitigation technologies related to Internal combustion engine based vehicles” (Y02T10/10), followed by “Technologies relating to chemical industry” (Y02P20/50) and to the “Reuse, Recycling or Recovery for solid waste management” (Y02W30/50); while Y02T10/10 remains in the top 3, “Wind energy (Y02E10/70) and “Other road transport mitigation technologies” (Y02T10/60) join the top group in the last timeframe (>2000 for each). The most ubiquitous technologies are related to wastewater treatment (Y02W30/50; Y02W10/10) and chemical industry (Y02P20/10) with 71 each; while Y02W30/50 remains, the top 3 is joined by two technology groups related to solar thermal (Y02E10/40; Y02B10/20) at the last timeframe (>92 for each).

Adopting a more ideal-typical view of the technology life cycle evolution, only relatively few technologies move away from their initial emergence stage in the first or second timeframe towards the diffusion or maturity stage in the last. For instance, out of the 74 technologies in the emergence phase at the first timeframe, only 16 technologies reach the diffusion and only 4 the maturity stage in the last. Taken together, this suggests that individual green technologies mainly follow the general trajectory of the overall development of all the other green technologies, simultaneously growing in patenting output and in their regional ubiquity.

Summary

Green technologies are characterised by a high technological heterogeneity, as can be derived by the volatility of the complexity ranking and is in line with earlier work (Santoalha & Boschma, 2019; Quatraro & Scandura, 2019). Furthermore, the most complex green technologies tend to be the ones that are also novel; this suggests that regions which possess the capabilities to introduce new-to-the world green technologies can also benefit from the associated economic benefits that can be derived from more complex technologies. The question of which regions are adding those technologies successfully justifies a closer look. Similarly, special attention has to be given to the role of green general-purpose technologies, as they might influence the available pathways. Accounting for the technology life cycle, most green technologies are relatively stable in their stages, with most technologies found at the Emergence stage, as was also confirmed by Barbieri et al. (2020) and the OECD (2015). The general green growth trajectory is driven by a simultaneous increase in ubiquity and patenting output, with only very few green technologies reaching the maturity stage over time;

while more and more regions thus follow green growth, there seems to be relative uncertainty about which green technologies might eventually become standardized and deployed at scale, which is in line with the inherent complexity of green technologies, driven by i.e. the need to comply with multiple technical-economic problems (Oltra & Jean, 2005) and with more stringent regulatory requirements (Carrillo-Hermossila et al., 2010) than in other domains (Fusillo, 2020; Fusillo et al., 2019). This might potentially also cause more dynamic patterns of entered, exited, and remaining green technologies compared to other domains, which again justifies the exploration of these in individual regions, as is proposed in this work.

4.2 Green Technology Fitness: Leading Regions

After this general overview of the green regional fitness and green technological complexity ranking, this part focuses on identifying which European regions have successfully diversified into more complex green technological capabilities over time.

Table 9: European Green Fitness Leaders at Timeframe Y1

NUTS2	Name	OECD	Rank	Green Output	Green Diversity	Ø Green Relatedness Density	
						RTA = 1	RTA = 0
FR10	Ile-de France	Hub	1	684.74	45	44.1	32.57
DE21	Upper Bavaria	Hub	2	415.08	43	39.22	30.74
DE25	Middle Franconia	Hub	3	220.25	40	39.9	31.26
FR71	Rhone-Alpes	Medium-Tech	10	243.93	35	37.16	30.35
DEA5	Arnsberg	Medium-Tech	11	109.74	38	44.38	35.74
DEA1	Duesseldorf	Medium-Tech	13	257.55	31	37.56	29.43
DE40	Brandenburg	Inertia	14	52.11	44	33.45	26.53
UKG	West Midlands England	Medium-Tech	18	68.72	34	37.8	30.83
FR82	Provence-Alpes-Cote d'Azur	Medium-Tech	21	86.95	31	35.47	28.07
SE31	North Middle Sweden	Service	22	41.17	19	28.85	21.74
ITC4	Lombardy	Traditional	25	187.83	29	38.97	31.27
ITI4	Lazio	Traditional	73	33.25	21	28.72	22.45
ES53	Balearic Islands	Inertia	125	3	9	8.33	5.43
HU33	Southern Great Plain	Primary	159	3.03	5	8.18	5.19
	Europe			Ø 40.76	Ø 18	Ø 30.3	Ø 19.4

Acknowledging the differences in regional innovation capacities and to allow for a diversity of insights into possible green growth diversification pathways, the leading and catch-up regions are identified as those within the top 10% of their respective innovation typology. The results are triangulated to keep only those regions that are among the top 10% in at least two of the typologies, while a complete overview can be found in Appendix IV. The triangulated results for the leading regions, along with their innovation typology from the OECD (OECD, 2011b) are presented in Tables 9 and 10. In the first timeframe, countries with the most leading regions are Germany (5), France (3) and Italy (2) and are mainly placed among the Top 25 in the green fitness ranking. Île-de France (FR10) and Upper Bavaria (DE21) have by far the highest green patent output, with around 685 and 415 and are also among the Top 3 in terms of the diversity with 45 and 43 green technology classes. Surprisingly, Brandenburg (DE40) as an Inertia region is competitive in 44 green technology classes, despite the very low patenting output of only around 52 and by far outperforms comparable regions, such as the Balearic Islands (ES53) or Southern Great Plain in Hungary (HU33).

Table 10: European Green Fitness Leaders at Timeframe Y4

NUTS2	**Name**	**OECD**	**Rank**	**Green Output**	**Green Diversity**	**Ø Green Relatedness Density**	
						RTA = 1	**RTA = 0**
DE25	Middle Franconia	Hub	1	675.02	73	36.87	30.96
FR10	Ile-de France	Hub	2	2001.55	63	35.86	28.72
DE21	Upper Bavaria	Hub	3	1403.03	61	38.3	31.78
FR71	Rhone-Alpes	Medium-Tech	4	1089.87	76	39.93	33.91
UKI	London	Capital	5	283.27	46	26.64	22.09
ITC4	Lombardy	Traditional	7	423.45	45	45.18	37.99
BE2	Flanders	Medium-Tech	8	448.73	36	34.66	29.26
UKK	South West England	Hub	10	398.69	49	30.94	25.06
UKG	West Midlands England	Medium-Tech	15	306.46	41	32.13	26.96
UKD	North West England	Medium-Tech	16	157.06	33	27.4	22.93
DEA5	Arnsberg	Medium-Tech	18	361.24	53	39.74	32.95
FR52	Brittany	Medium-Tech	19	135.93	32	20.66	15.97
ITC1	Piemonte	Traditional	24	299.77	54	39.47	33.75
ITI4	Lazio	Traditional	30	113.05	50	34.33	28.94
PL12	Masovia	Primary	46	52.71	35	28.79	22.08
PL21	Lesser Poland	Primary	86	32.88	27	23.37	19.42
PL11	Lodz	Primary	138	23.29	19	20.97	15.95
	Europe			Ø 129.26	Ø 27	Ø 28.12	Ø 18.44

In terms of the average green relatedness density, almost all regions have far higher density values; disregarding ES53 and HU22, for the existing portfolios, only North

Middle Sweden (SE31) and Lazio (ITI4) are somewhat below the European average, suggesting a slightly less related green technology portfolio. Turning to the last timeframe, countries with the most leading regions are now the UK (4), Germany, France, Italy, and Poland (each 3), suggesting an increased geographic spread of green complex capabilities. While the average green patent output and diversity has increased in Europe, the average green relatedness density has slightly decreased; this could be caused by the high technological heterogeneity and an increase of green technologies at the emergence stage. Again, Île-de France (FR10) and Upper Bavaria (DE21) have by far the highest green patent output, with around 2002 and 1403. The regions with the highest diversity on the other hand are now Middle Franconia (DE25) and Rhone-Alpes (FR71) with 73 and 76 green technologies. Despite being only the fourth region by green patent output, Middle Franconia is the most fit region. Only four regions have a lower patenting output than the European average, with all three Polish regions, while only Lodz (PL11) also has a lower-than-average diversity. Somewhat more surprising is Brittany (FR52) which has the third-lowest diversity number of the leading regions, but is placed far above at fitness rank 19 compared to rank 86 and 138 for Lesser Poland (PL21) and Lodz; also in terms of its average green relatedness density, Brittany is far below the European average, and on a similar level to Lodz. This points to a comparatively low relatedness of green technologies in their portfolio. On the other hand, two Traditional Manufacturing regions, the Lombardy (ITC4) and Piemonte (ITC1), as well as two Medium-Tech regions, Rhone-Alpes, and Arnsberg (DEA5) have a much denser green technology portfolio.

Summary

Identifying the green technology leaders by their innovation typology reveals several aspects: 1) that the general patterns of higher patenting rates, higher green diversity and higher green relatedness density contribute to more complex green capabilities, as discussed in 4.1.1, seems to be especially true for the leaders as compared to Europe; 2) changes among the leaders are more considerable with around half the regions newly joining, in particular from the UK and Poland, with three new entries each. This could potentially be driven by national green industrial policies, pushing those regions to the top of their respective groups; 3) of all the regions being among the leaders, Brittany looks like the most unlikely one, in particular due to the far-below green relatedness density, even compared to the Polish Primary-sector-intensive regions. Thus, its green growth diversification pathways seem particularly promising.

4.3 Green Technology Fitness: Catch-Up Regions

For the catch-up regions, that are within the top 10% of their respective innovation typology by ranking improvements, the triangulated results are presented in Table 11.

Table 11: European Green Fitness Catch-Ups

NUTS2	Name	OECD	Δ Rank	Δ Green Output	Δ Green Diversity	Δ Ø Green Relatedness Density	
						RTA = 1	RTA = 0
PL12*	Masovia	Primary	-104	35.54	22	12.01	10.58
ES21	Basque Country	Medium-Tech	-93	100.2	33	7.47	8.6
FR52	Brittany	Medium-Tech	-92	112.58	20	-1.59	-1.18
PL21*	Lesser Poland	Primary	-70	25.88	20	10.21	10.3
BE1	Brussels	Capital	-64	62.58	25	3.87	4.98
DK05	North Jutland	Service	-53	81.96	31	4.77	4.53
AT12	Lower Austria	Traditional	-49	107.99	20	0.69	2.44
ITH4	Friuli Venezia Giulia	Traditional	-49	71.34	13	-1.27	-0.46
ES51	Catalonia	Medium-Tech	-47	272.56	17	4.59	5.43
ITC3	Liguria	Medium-Tech	-47	64.14	30	4.81	5.35
ITH2	Trentino	Traditional	-45	21.28	14	7.84	7.04
DE22	Lower Bavaria	Hub	-43	76.52	24	-0.71	1.21
FR81	Languedoc-Roussillon	Inertia	-43	103.41	37	5.02	5.5
ITI1	Tuscany	Traditional	-47	92.86	13	2.11	3.47
UKD	North West England	Medium-Tech	-43	60.79	14	-3.39	-1.99
BE3	Wallonia	Medium-Tech	-41	129.81	26	5.94	6.16
FR43	Franche-Comte	Medium-Tech	-41	29.73	15	3.39	4.48
DE91	Braunschweig	Medium-Tech	-40	49.02	12	0.2	1.59
PL11*	Lodz	Primary	-45	19.46	15	10.72	10.04
ES24	Aragon	Inertia	-30	40.17	14	2.6	4.67
	Europe**			Ø Δ 88.5	Ø Δ 9	Ø Δ -2.18	Ø Δ -0.96

**Regions with initial rank position in Y2 | **European averages excluding regions with initial ranks at Y2*

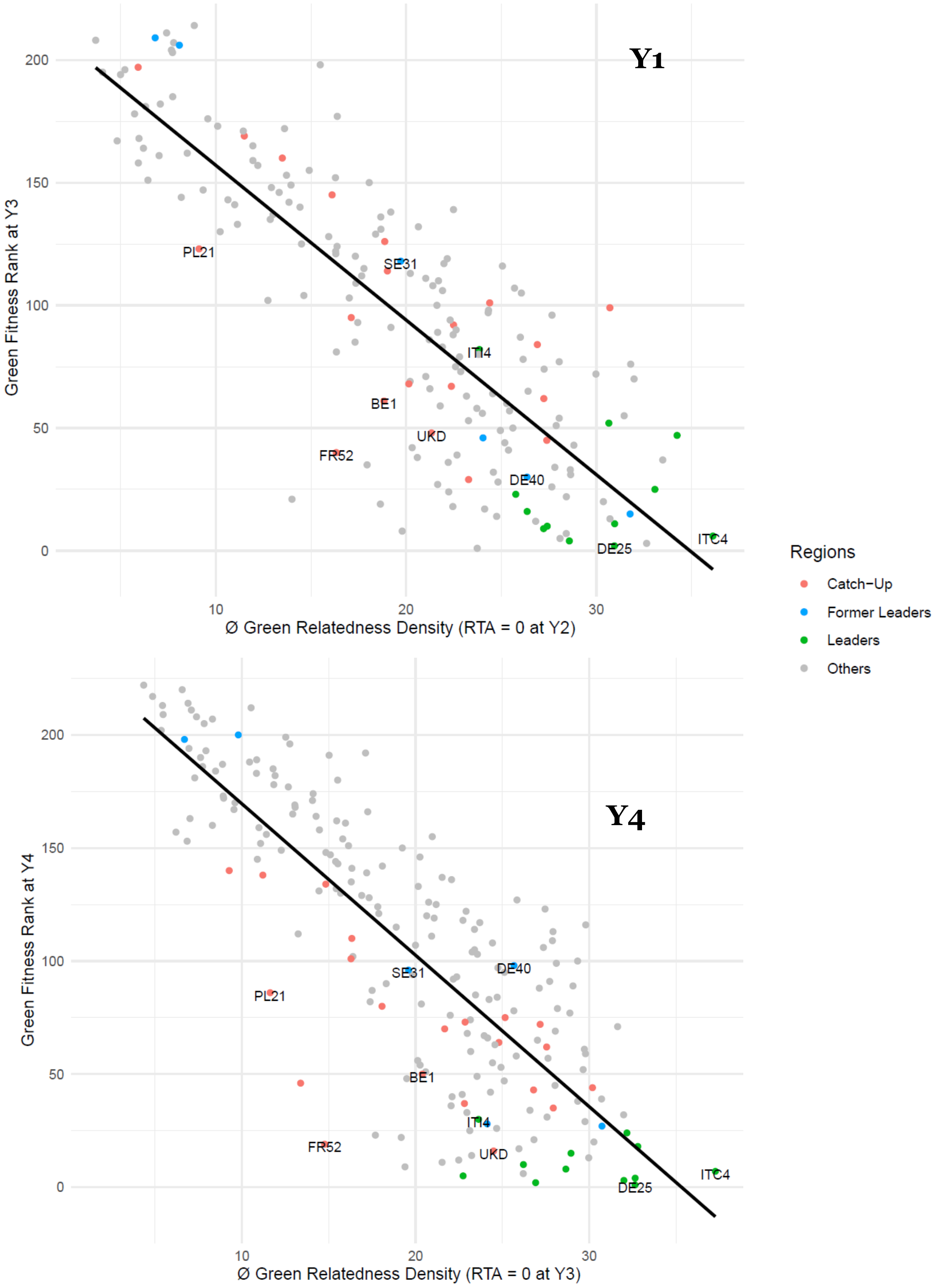
To allow for novel regions, the overall ranking improvement between each regions' initial fitness rank timeframe and the last timeframe was considered. Countries with the most catch-up regions are Poland, Spain, France, and Italy (3 each) followed by Germany and Belgium (2 each). The highest improvement in terms of ranking spots was achieved by Masovia (PL12) with 104, followed by Basque Country (ES21) and Brittany (FR52) with 93 and 92, respectively. Of the top 5, the two Polish regions are classified as Primary-sector-intensive regions, whereas the Southern European regions are Medium-Tech and Brussels (BE1) a Capital region. This might point to differences in terms of whether the ranking improvements were driven because of a higher general innovation capacity or despite a lack thereof. Among the catch-up regions, Catalonia (ES51) has experienced the highest growth in green patenting output by around 273. In terms of most added technology classes, Languedoc-Roussillon (FR81) takes the top spot with an increase of green diversity by 37, followed by Basque Country with 33, which is far more than the 9 on average in Europe.

While most of the catch-up regions have considerably increased the green technological relatedness density of their portfolio, most notably the Polish regions, a few regions have decreased their green technological relatedness density, despite their significant improvements in fitness ranking spots. North West England (UKD) experienced the highest decrease, followed by Brittany and Friuli Venezia Giulia (ITH4), more in line with the average decrease in Europe overall. Again, this might point to differences on the importance of related diversification for green growth for particular regions.

Building on the maps in Figure 3 and 5, the relationship between the average relatedness density with the subsequent fitness rank in the following timeframe is shown in Figure 8, to more systematically account for this relationship for leading and catch-up regions in particular. Assuming that an increase in green relatedness density results in an improved green fitness rank (for simplicity reasons in a linear way), there seems to be a divide between two types of Catch-Up regions in a): the ones, which are above the diagonal line, where the green fitness rank is lower than what could be expected by the comparatively high green relatedness density; and the ones, which are below the diagonal line, where the green fitness rank is higher than what could be expected by the comparatively low green relatedness density.

While the first group seems to be successful in leveraging on their capabilities over time, moving closer to their predicted fitness rank, the second group of regions seem to systematically outperform this relationship, such as Lesser Poland (PL21), Brittany (FR52), Brussels (BE1) and North West England (UKD). In that regard they seem similar to the Leading regions, where in the last timeframe especially, this pattern can be observed for almost all regions, including Lazio (ITI4) and Middle Franconia (DE25), with the exception of Lombardy (ITC4). On the other hand, former leaders such as Brandenburg (DE40) seem to have lost their ability to outperform this

Figure 8: Relationship between Average Green Relatedness Density and Green Fitness Rank



relationship, while North Middle Sweden (SE31) seems to align with it quite closely. In addition, the relationship between the average green relatedness density and the subsequent green fitness rank seems less predictive for higher fitness ranks in the last timeframe (i.e. Top 50).

The question is then, how those particularly successful regions have moved towards a more complex green technology portfolio; to explore this, Brittany (FR52), Brussels (BE1) and Lesser Poland (PL21) are selected. This is due to them being among the top 5 regions of overall ranking improvements, have consistently improved their fitness rank between all timeframes, are fairly diverse in terms of both their geographic dimension, i.e. from three different countries, and one being from Eastern Europe, as well as in their general innovation capacity and have been successful despite their comparatively low green average relatedness density.

Summary

Identifying the green technology catch-ups by their innovation typology reveals the following aspects: 1) It seems possible to considerably improve the complexity of regional green capabilities over time, fairly independent of a regions' general innovation capacity; in fact, the top 10 of ranking improvements contain Primary-sector intensive regions, Medium-Tech regions, a Capital region, a Service region as well as Traditional Manufacturing regions. This observation holds promise with regards to directing economic capabilities in the direction of green growth for all regions. 2) In terms of catch-up pathways, there seems to be a divide between regions that have increasingly leveraged on their capabilities over time, as evidenced by their comparatively higher green relatedness density, and regions that have systematically outperformed this relationship. Thus, the latter seem to have successfully deviated from the principle of relatedness and exploring the cases of Brittany (FR52), Brussels (BE1) and Lesser Poland (PL21) is especially promising to uncover these pathways to success as a blueprint for other regions.

Overview of Selected Regions

To complement the mapping and exploratory account of the green technology spaces, a first overview of the regional and technological dimensions within those regions is provided, which already captures some of the expected dynamics in a concise way. As an upper benchmark, this is also done for Middle Franconia (DE25) as the leading region with the most complex green capabilities at the last timeframe.

Middle Franconia

Middle Franconia is a Hub region, which is characterized as a top knowledge and technology region by the OECD, with the highest average levels of R&D and patenting intensity and a significant share of manufacturing in high-technology sectors (OECD, 2011). It is located in the federal state of Bavaria, in the south of Germany, and includes the cities of Nuremberg, Erlangen and Fürth.

Regarding its green technology portfolio, as shown in Table 12, Middle Franconia has consistently added new green technology groups which are produced with RTA and has steadily improved its fitness ranking position from 3 to 1. At the same time, the relatedness density has decreased, in line with the general decrease observed in Europe. The complexity distribution across the complexity quartiles within the green technology portfolio is fairly stable over time, ranging between 22 to 30% for each quartile; only between 2005-2009 the top complexity quartile is significantly smaller, but without affecting its overall rank position. Most green technologies are in the Emergence (TLC =1) stage of the technology life cycle, in line with the generally large group of technologies at this stage (see Figure 7). Furthermore, Middle Franconia is fairly active with new-to-the world technologies (TLC =0), which make up between 3 and 11% of the regional green technology space.

Table 12: Green Technology Portfolio of Middle Franconia

Period	Rank	# RTA	Ø Relatedness Density		Complexity (%)				Green TLC (%)				
			RTA=0 (SD)	RTA=1 (SD)	1	2	3	4	0	1	2	3	4
1995-1999	3	40	31.26 (2.10)	40.00 (5.76)	23	28	25	25	0	40	5	23	33
2000-2004	3	57	30.95 (1.85)	38.52 (4.69)	23	30	26	21	11	40	4	23	23
2005-2009	2	66	32.64 (1.47)	38.63 (3.67)	15	27	27	30	6	42	2	21	29
2010-2014	1	73	30.00 (1.73)	36.87 (3.71)	22	23	27	27	3	45	3	22	27

Overall, Middle Franconia's technology space is fairly balanced across the complexity quartiles and the respective technology life cycle. Importantly, a higher green fitness rank is not associated with possessing competitive advantages in only very complex technologies, but with possessing those advantages across the whole technology space, consistent with earlier findings (Hausmann et al., 2014; Hidalgo & Hausmann, 2009). After establishing this upper benchmark, the catch-up regions are discussed.

Brittany

Brittany is considered a Medium-tech manufacturing and service provider region, which are mainly industrial production regions in middle-income countries; these are characterised by a strong medium-low and medium-high-technology industry base and relatively high knowledge absorptive capacities (OECD, 2011b). Brittany is located in the Northwest of France and includes the cities of Nantes, Rennes, and Brest.

As shown in Table 13, the green technology portfolio of Brittany changes considerably over time, which is in line with the fitness rank improvement from rank 111 to rank 19. While the green technology portfolio did not contain any technologies at the highest complexity quartile between 1995 and 1999, there is a steady increase of the share between the timeframes, even surpassing that of Middle Franconia in the last. These however seem to be largely driven with a simultaneous decrease in the second complexity quartile; compared to Middle Franconia, the portfolio evolution is more volatile, with the lower half of the complexity quartiles containing between 50-75% at all timeframes. In line with the increased complexity, there is a steady increase of Emergence technologies from 8% to 41% of the portfolio, coupled with a considerable decrease of Maturity technologies from 67% to 19%. Regarding new-to-the-world technologies, Brittany is also active, albeit on a lower scale than Middle Franconia.

Table 13: Green Technology Portfolio of Brittany

Period	Rank	# RTA	Ø Relatedness Density		Complexity (%)				Green TLC (%)				
			RTA=0 (SD)	RTA=1 (SD)	1	2	3	4	0	1	2	3	4
1995-1999	111	12	17.16 (2.25)	22.25 (1.77)	0	25	8	67	0	8	0	25	67
2000-2004	41	26	16.33 (1.77)	21.01 (3.69)	8	27	27	38	4	19	4	42	31
2005-2009	40	26	14.76 (1.84)	19.33 (2.41)	15	35	23	27	4	35	0	38	23
2010-2014	19	32	15.97 (1.63)	20.66 (4.10)	28	9	34	28	3	41	6	31	19

Brussels

Brussels is characterised as a knowledge-intensive capital district, which is densely populated with high R&D and patenting intensity. Furthermore, the workforce is highly educated, and the share of services is comparatively high (OECD, 2011b). Brussels is the capital of Belgium.

As shown in Table 14, Brussels has added more green technologies that they produce with RTA than Brittany and has on the opposite, increased the average relatedness density of its green portfolio. Compared to Brittany, it has a much lower share of technologies at the highest complexity quartile; similar to Brittany, the increased share at the top quartile at the last timeframe is associated with a simultaneous decrease at the second complexity quartile. Regarding new-to-the-world technologies, Brussels is less consistent than Brittany with only two technologies at that stage in 2005-2009

(6%). Also, the increase of technologies at the emergence stage is less steep, mainly because the initial share was already fairly high with 19% compared to 8% in Brittany.

Table 14: Green Technology Portfolio of Brussels

Period	Rank	# RTA	Ø Relatedness Density		Complexity (%)				Green TLC (%)				
			RTA=0 (SD)	RTA=1 (SD)	1	2	3	4	0	1	2	3	4
1995-1999	114	16	16.39 (2.34)	22.43 (2.36)	6	0	38	56	0	19	0	13	69
2000-2004	90	24	18.84 (2.62)	24.48 (2.18)	0	13	42	46	0	25	0	25	50
2005-2009	61	36	20.39 (2.55)	25.39 (2.23)	11	25	19	44	6	28	3	19	44
2010-2014	50	41	21.37 (2.22)	26.30 (1.78)	15	10	34	41	0	29	0	32	39

Lesser Poland

Lesser Poland is a primary-sector intensive region, which consist of Southern and Eastern European regions with low population density, with a significant share of economy in primary sector or low-technology manufacturing. Furthermore, the R&D and patenting intensity is lowest of all typologies (OECD, 2011b). Lesser Poland is located in Southern Poland and includes the cities of Krakow and Lublin.

As is shown in Table 14, Lesser Poland has considerably improved its ranking position over a comparatively shorter time period. It has added the same number of green technologies which it produces with RTA as Brittany, and in so doing, has strongly increased the average green relatedness density. Compared with Brussels and Brittany, there is no decline of the second complexity quartile over time, suggesting that the highest complexity quartile remains fairly unattainable. Nonetheless, it has a similar distribution of technologies at the lower half of the complexity ranking like Brussels; also, the distribution across the lifecycle looks fairly similar, in particular as it also included a considerable share of emergence technologies from the beginning (14%). Other than Brussel or Brittany, Lesser Poland does not seem to possess the capacities to engage in new-to-the-world technologies.

Table 15: Green Technology Portfolio of Lesser Poland

Period	Rank	# RTA	Ø Relatedness Density		Complexity (%)				Green TLC (%)				
			RTA=0 (SD)	RTA=1 (SD)	1	2	3	4	0	1	2	3	4
1995-1999	-	-	-	-	-	-	-	-	-	-	-	-	-
2000-2004	156	7	9.11 (1.66)	13.16 (1.05)	0	0	29	71	0	14	0	14	71
2005-2009	123	14	11.63 (1.95)	15.20 (2.00)	7	29	29	36	0	21	0	36	43
2010-2014	86	27	19.42 (2.29)	23.37 (1.40)	7	22	30	41	0	30	0	37	33

Summary

This suggests that the pathways could look fairly similar for Brussels and Lesser

Poland, while Brittany could be a somewhat different case; also, as the relatedness density has increased for both, while quite the opposite has happened for Brittany. Furthermore, higher complex green capabilities seem to also be related to more green capabilities in general, such that all regions seem to have a fairly balanced distribution across the complexity quartiles, even for the leading region, but with limitations to what is attainable at the highest complexity quartile for Lesser Poland and Brussels. Additionally, of the catch-up regions, only Brittany seems to possess the capacities to introduce new-to-the world green technologies. Building upon those general observations, the following sections provide a more systematic account.

4.4 The Green Technology Space of Catch-up Regions

Turning to the second research question, what the similarities and differences between catch-up regions with regards to their green diversification pathways in the technology space are, the technological dynamics for each of the selected catch-up regions are mapped out over time. The aim is to identify how specifically those regions have navigated and successfully leveraged on the technological dimensions of relatedness, complexity, and technology life cycle to explain the empirical patterns that have resulted in the considerable improvement of those regional green capabilities over time and to derive explanations of how those technological dynamics might have been embedded in the regional dimension, specifically with regards to the general innovation capacity. Uncovering these pathways to success holds promise in directing regions to develop such more complex capabilities, in line with the notion of green growth.

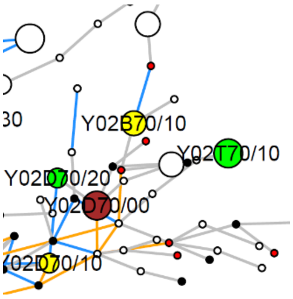
This is done using a combination of two figures between each of the timeframes for each region. The first figure is depicting the European technology space, which is based on the relatedness measure φ and mapping the technological dynamics of each region within it. The nodes are color-coded according to the changes that occurred between two timeframes as follows:

Green Tech Dynamics
🟨 Remained
🟩 Entered
🟫 Exited

Non−Green Tech Dynamics
⬛ Remained
🟥 Entered

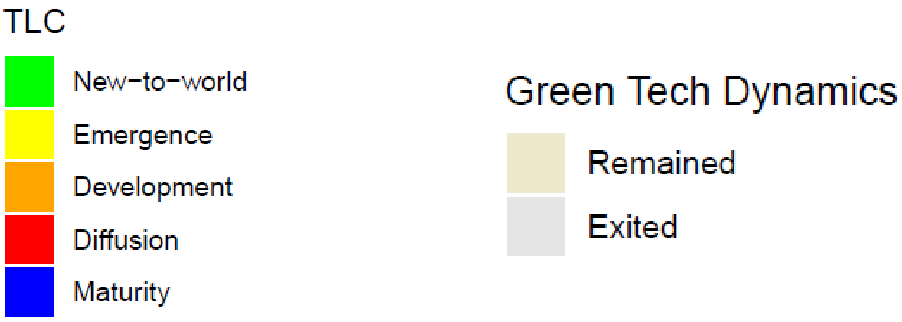
Furthermore, the node size corresponds to the complexity of each of the green technologies, with larger nodes belonging to a higher complexity quartile. For reference, a visual example is provided in Figure 9.

Figure 9: Example Figure 1 of the Green Technology Space



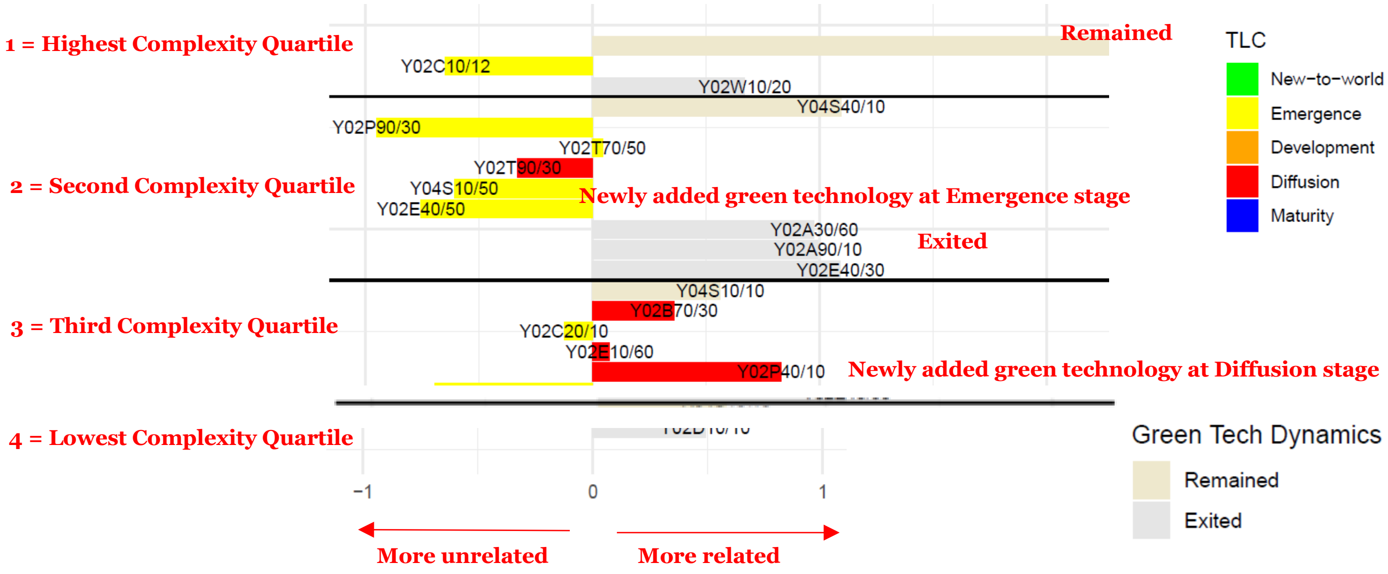
The second figure represents these dynamics using the standardized relatedness density of each of the exited, entered and remaining green technology in a region. In addition, the complexity quartile for all the exited, entered and remaining green technologies is provided, while the technology life cycle is depicted for all newly entered green technologies. As a reminder, the standardized relatedness density is calculated with the mean across the exited, entered and remaining green technologies within each region and is proposed as a way to control for the relative variation of this measure in each region; with higher positive values indicating a higher degree of relatedness and lower negative values indicating a higher degree of unrelatedness as compared to the regional technology portfolio.

The bars are color-coded to indicate 1) the technology life cycle for all the newly entered green technologies and further to 2) show the remained and exited green technologies as follows:



Importantly, within each complexity quartile, the order of the technologies is first, the remained, second all newly added, third the exited green technologies. For reference, a visual example is provided in Figure 10.

Figure 10: Example Figure 2 of the Green Technology Space



To capture the time dynamics, the relatedness in the technology space representation is set equal to timeframes Y2, Y3 and Y4, while the standardized relatedness density is shown for the respective previous timeframe Y1, Y2 and Y3. The complexity and technology life cycle are again equal to Y2, Y3 and Y4.

In cases of new-to-world technologies which do not possess a standardized relatedness density value for their previous timeframe, the average of all the other technologies is taken to avoid inflating the measure across the timeframes; as a consequence, only the relatedness in the technology space and not the standardized relatedness density is informative for those technologies.

While no propositions in terms of green growth diversification pathways along the regional and technological dimensions were previously made, analysing the potential similarities and differences requires the use of some established notions of the pathway literature. Grillitsch & Hansen (2019), while based on the meso-level of green industries, provide some useful starting points which are adopted to the dynamics of the technology space and the level of green technologies studied here.

Path emergence is defined in terms of newly added green technologies, which occur in relative isolation in the technology space. *Path development* is defined in terms of the subsequent branching process from those initial path emergence technologies, where new green technologies are entered. *Path upgrading* is defined in terms of a substitution effect from lesser complex green technologies, which are exited, to more complex green technologies which are entered, and which are closely related in the technology space. *Path diversification* is defined in terms of those branching processes that are neither the result of an initial path emergence, nor result in the complexity substitution effect of path upgrading. Importantly, all those pathways are defined and visible only in terms of the relatedness in the technology space.

Similarities and differences between the catch-up regions are then studied in terms of 1) whether those pathways can be observed in the region, 2) how the dimensions of complexity, relatedness as measured by the standardized relatedness density within the region, and the stages of the technology life cycle have affected those pathways and 3) how those technological dynamics of the pathways might have been embedded in the differing regional innovation capacity. In the following, a detailed account of each region's dynamics is provided.

4.4.1 Brittany Technology Spaces

In **Brittany's technology space at Y2 (Figure 11),** three clusters can be observed. The first one is in the dense core, with comparatively simple green technologies **(I)**; here, Brittany exits more green technologies than it enters and successfully spreads out to some fairly related, but more complex technologies. This is consistent with *path upgrading*. Here, Y02W30/40 appears to have a bridging role between the dense core and the newly added technologies; interestingly Y02B10/70 and Y02C20/10 are both already in their Diffusion phase, while belonging to the third and second complexity quartile, respectively. This could point to a potential pathway mechanism, of relying on weakly related, yet comparatively established technologies to upgrade the complexity of the green technology portfolio.

The second cluster is to the north of the core, where a number of green technologies related to Information and Communication Technologies Y02D are appearing **(II)**. Here, Brittany already possesses a very dense structure of non-green and very related technologies, with a number of newly added non-green technologies in parallel as well, pointing towards *path diversification*. The newly added green technologies appear almost coupled, where lower-complexity, related technologies seem to provide a steppingstone for high-complexity, unrelated technologies; for instance, the weakly related Y02D10/10 in the Development stage enabling the reach of highly-complex, yet unrelated Y02D10/20 in the Emergence stage. This relationship is even stronger for the more related technology Y02D50/10, coupled with the highly unrelated Y02D50/30. This could indicate yet another pathway mechanism, of coupling (higher) unrelated diversification opportunities with (higher) related branching within a dense technology cluster.

The third cluster appears to the south-west of the core, with a number of technologies related to energy generation (Y02E) and Smart grids (Y04S) appearing **(III)**. While Brittany exits Photovoltaic Y02E10/50 it enters Energy storage Y02E60/10 and enabling technologies related to Smart grids and renewable energy transmission in general Y02E60/70 as well as in buildings Y02B70/30. Interestingly, all these technologies are already at increased life cycle stages but are still mainly in the second and third complexity quartile. As this pathway seems to have less to do with an upgrading towards more complex technologies per se, it is rather a case of *path diversification* together with a re-orientation of the portfolio.

Turning more to the role of relatedness, it is thus rare to observe unrelated diversification cases that are not coupled within the technology space. Nonetheless, for Brittany these cases exist, such as Applications of fuel cells in buildings Y02B90/10 or the new-to-the world technology to reduce energy consumption in distributed systems Y02D10/30 which is at the periphery of the technology space. These isolated instances seem to be the ideal-type *path emergence* pathways; the interesting question for those is whether these can be sustained and developed over time. On the other hand, relatedness of varying degrees plays an important role in especially the third and fourth complexity quartile, while a more mixed approach seems important for higher-complexity quartiles; interestingly, it seems that Brittany has to some extent compensated the fairly weak relatedness of technologies at the second complexity quartile by focusing on green technologies at the Diffusion stage, thus presumably profiting from the inflow of technological knowledge produced outside of the region.

Over time, the technology space in general becomes more clustered and separated into branches. In **Brittany's technology space at Y3 (Figure 12)** the core is again mostly characterized by exited green technologies, consistent with further *path upgrading* **(I)**. As for the cluster around the Information and Communication Technologies Y02D **(II)**, it largely still exists at the north east of the technology space, although some of the technologies seem to be substituted for similarly complex technologies, which in this case again is rather characterised by *path diversification* together with a re-orientation of the portfolio. The cluster related to energy generation Y02E and Smart grids Y04S on the other hand disperses, with two novel energy generation technologies Y02E10/20 and Y02E40/60 appearing to the east, as

Figure 11: Brittany Technology Space (Y2)

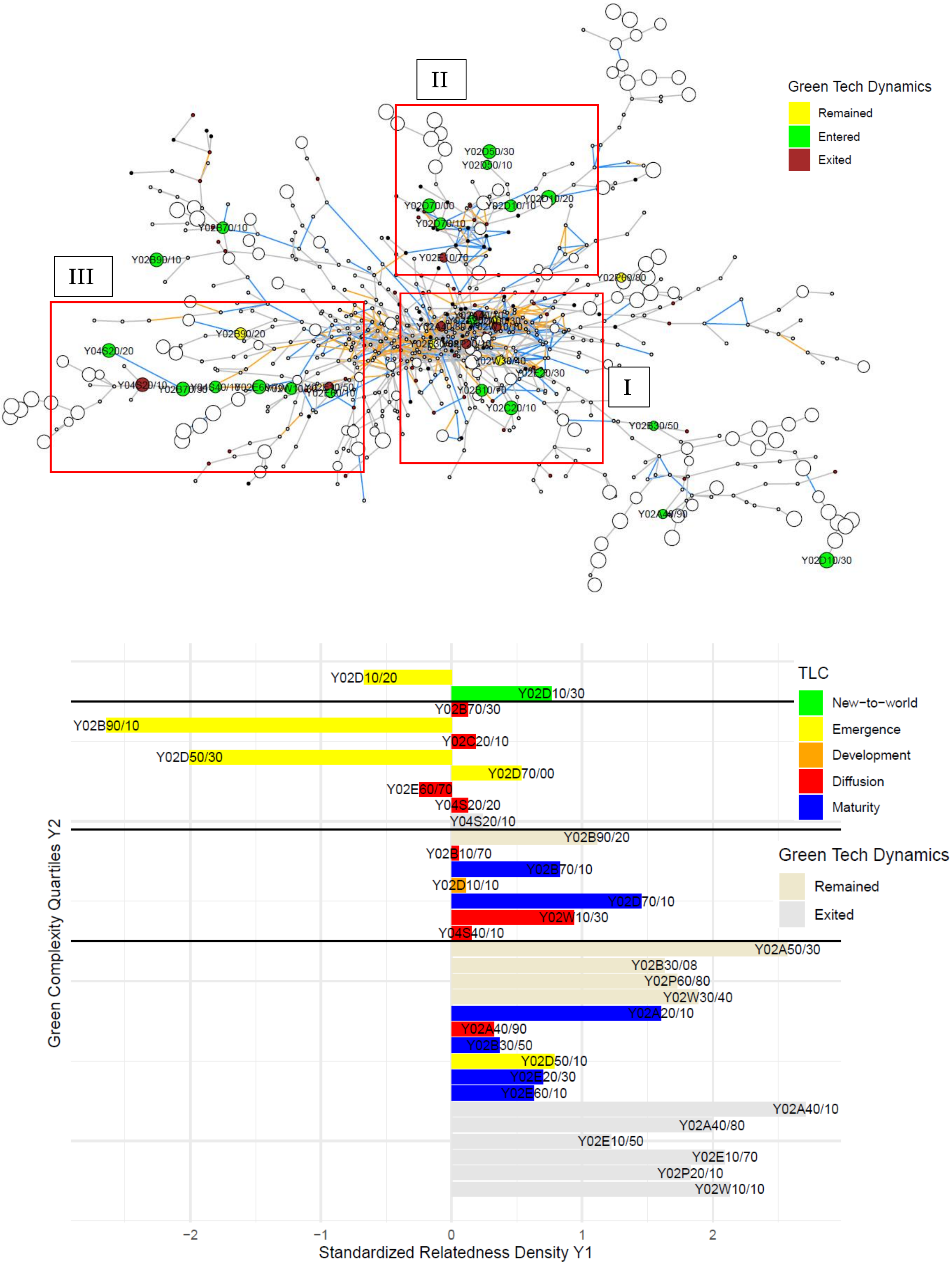
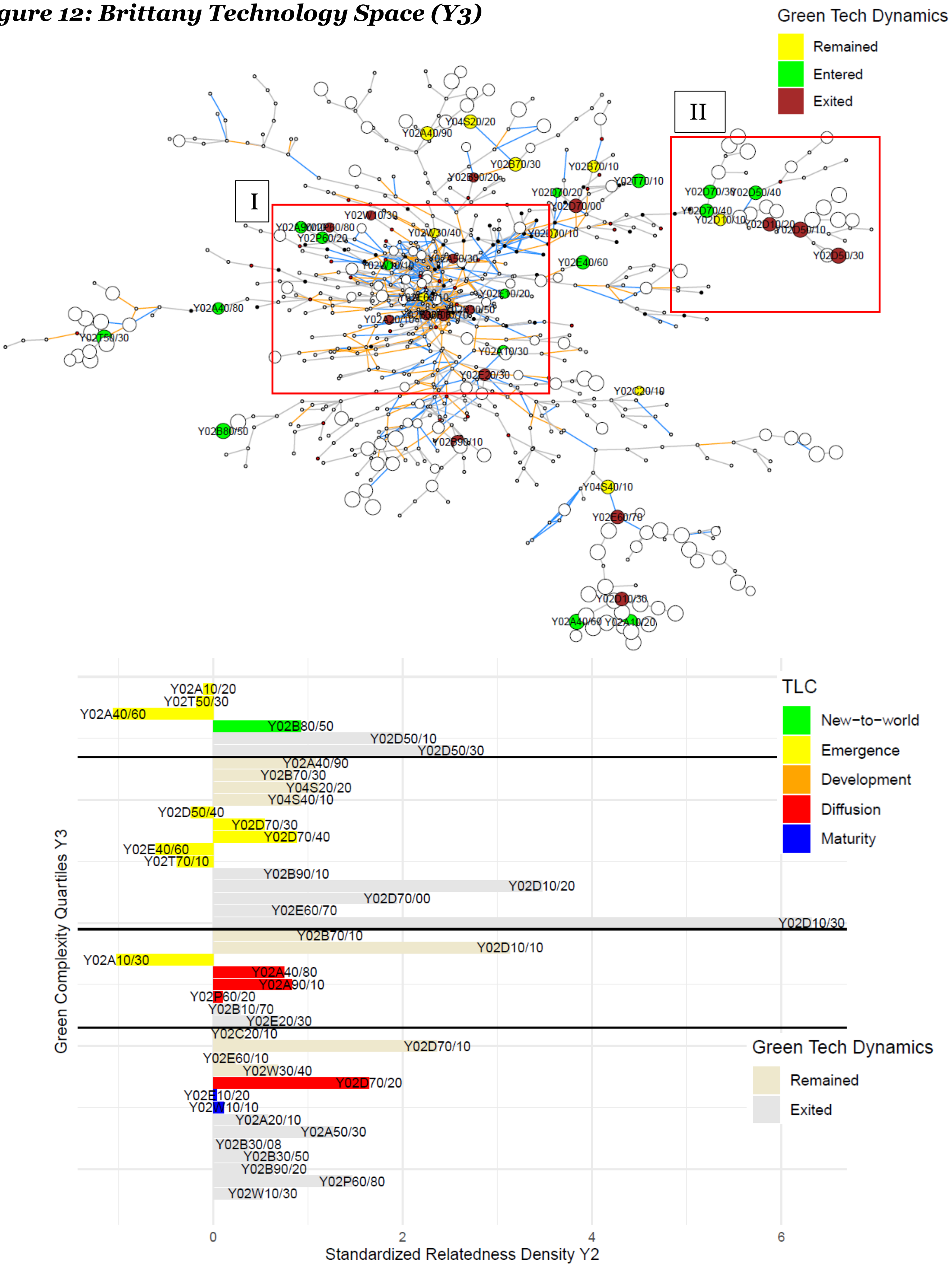


Figure 12: Brittany Technology Space (Y3)



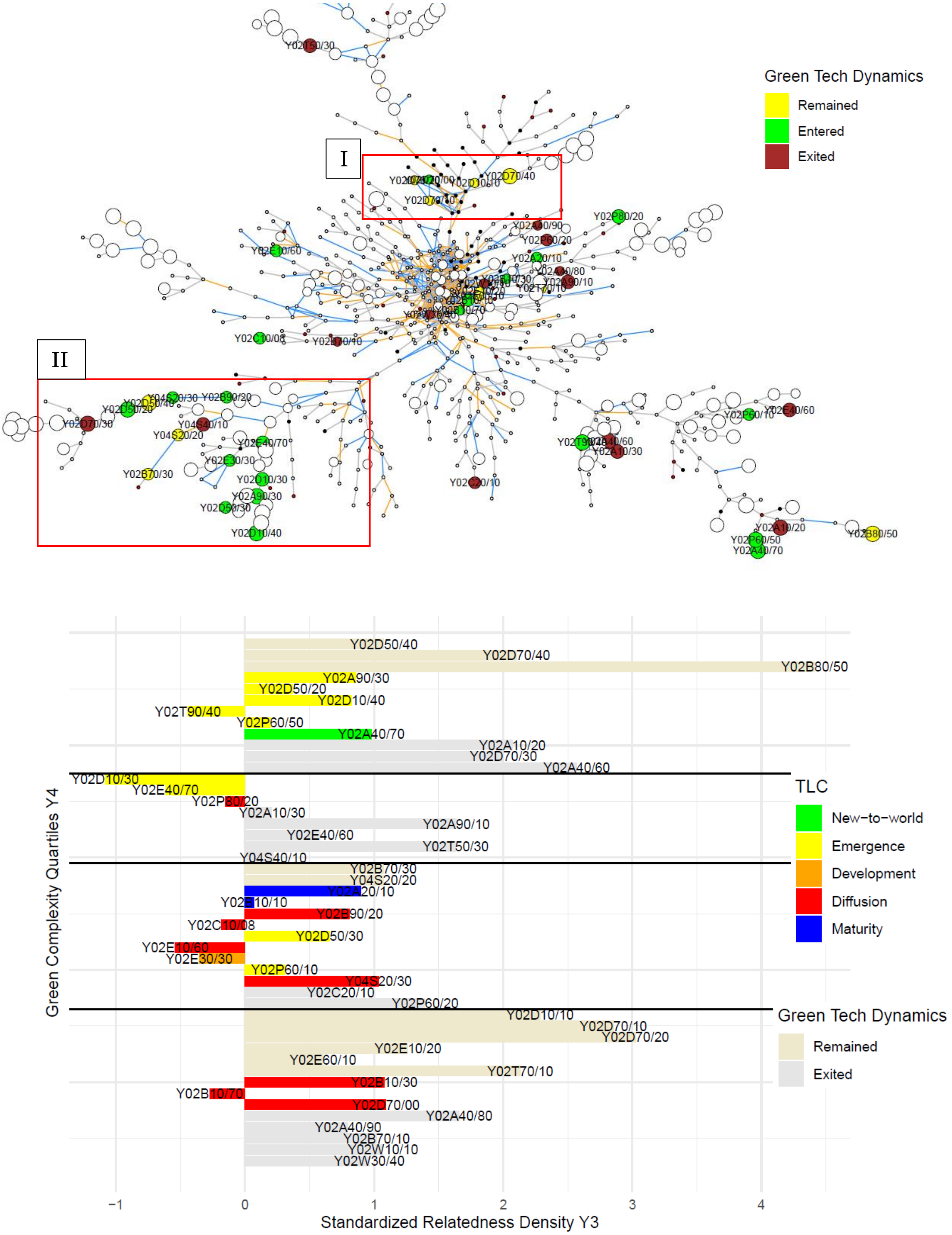
part of the *path upgrading* of the core, while others are exited at the south. On the other hand, Y04S40/10 appears to have a bridging role between the cluster in the south and the rest of the network.

While at this timeframe Y3, both previously described isolates Y02D10/30 and Y02B90/10 are abandoned again, some complex and largely unrelated technologies, such as some adaptation technologies Y02A10/20 and Y02A40/60 in the south, a wing lift efficiency technology in the west Y02T50/30 and a new-to-the-world technology related to the thermal performance of buildings Y02B80/50 again appear as isolates, constituting *path emergences*.

In general, the technology lifecycle stages become more aligned with the complexity quartiles, as Brittany no longer relies on the Diffusion stage for its newly entered green technologies in the more complex quartiles. Furthermore, even in the third complexity quartile, Brittany now engages in unrelated diversification. Also, the relative importance of exits from technologies seems to increase; in the highest complexity quartile for instance, the two abandoned technologies are of lower complexity compared to the four newly entered, with the same pattern found in the third quartile. In the second complexity quartile on the other hand, the four remaining technologies are among the six least complex technologies in this quartile, while the newly entered and exited technologies differ only slightly. This last point could be suggestive of yet another pathway mechanism towards green growth, which could be characterized as strategically re-orientating the technology portfolio through similarly complex exits and entries, while using comparatively lower complex technologies as steady anchor points throughout this process.

In **Brittany's technology space at Y4 (Figure 13)**, most of the technologies at the highest complexity quartile, are those related to Information and Communication Y02D, which is now largely divided into two parts: one in the north, where most of these are remaining technologies **(I)** and a new one to the south west **(II)**, where the majority are new entries, such as Y02D10/40 or Y02D50/20, with both clusters showing *path diversification*. Throughout the technology space, it becomes more difficult to distinguish *path emergence* from *path diversification* with re-orientation of the portfolio as most newly added green technologies seem somewhat closer to simultaneously exited green technologies. Compared to Y3, almost all the described isolates are abandoned again, besides Y02B80/50 which however remains an isolate at the periphery of the technology space. Thus, it seems relatively difficult to

Figure 13: Brittany Technology Space (Y4)



embark on sustainable *path development* from largely isolated green technologies.

Similar to the described mechanism of strategically re-orientating the technology portfolio through similarly complex exits and entries, while using comparatively lower complex technologies as steady anchor points, the same is observed for the highest complexity quartile in Y4, while the second and third complexity quartile are almost completely substituted, with considerably more new entries across the whole lifecycle in total especially in the third complexity quartile. This suggests that the entry dynamics have substantially increased over time for Brittany. As for the relatedness, unrelated diversification as measured by the standardized relatedness density becomes more important at all levels of complexity; this however can also be partly attributed to the measure, as some highly related technologies, such as Y02B80/50 in the highest complexity quartile, are quite influential outliers.

Summary: Brittany's Green Growth Diversification Pathway

Brittany's pathway towards more complex green technologies is mainly characterized by consistent *path upgrading* in the core and *path diversification* within clusters at different parts of the technology space. The increasingly sparse core and the distributed clusters could explain the decline of average relatedness density over time. On the other hand, while several instances of *path emergences* were observed, especially at the two later timeframes, subsequent *path development* from those more isolated green technologies did not seem to be successful, as they were mostly exited again or only remained, albeit complex, isolates.

Focusing on the pathway mechanisms, and crucially at the beginning, Brittany developed more complex capabilities by relying on entries into comparatively mature green technologies at the diffusion stage, and thereby re-orientating its green technology portfolio; this would suggest that building upon knowledge developed elsewhere can be a successful strategy. Furthermore, and also at the beginning, more unrelated diversification opportunities were coupled with more related entries within the technology clusters. These seem to have been the most important drivers towards acquiring more complex green capabilities, also evidenced by the fitness rank jump from 111 in Y1 to 41 in Y2 (Table 13).

This initial inflow of more complex capabilities might have also facilitated the successful engagement with 1) more unrelated technologies at earlier stages of the technology life cycle and 2) the increased number of *path emergences* at later timeframes. In addition, over time, a third mechanism towards green growth, characterized as the strategic re-orientation through exits and entries and using lower complex technologies as anchor points became important, also highlighting the need to not only consider related or unrelated new entries as branching opportunities, but also the strategic role which technological exits and anchoring technologies can have beyond their role in *path upgrading*; such that despite the high volatility of the complexity ranking this seems to have enabled Brittany to improve their fitness rank towards rank 19.

At the green technology level, the Information and Communication Y02D cluster played a steadily crucial role mainly for *path diversification* within the cluster, while contrary to what was expected, enabling technologies played a comparatively little role for Brittany's green growth, similar to the engagement in new-to-the world technologies.

4.4.2 Brussels Technology Spaces

The **Brussels Technology Space at Y2 (Figure 14)** appears relatively less clustered compared to Brittany, and thus the region possesses green technologies across many different parts of the technology space. The core is denser than Brittany's but also shows *path upgrading*, with lesser complex technologies being substituted for more complex ones at the periphery of the core **(I)**. Furthermore, the exits are not solely confined to the core, but already take place also at more peripheral parts, differentiating between instances of *path upgrading* towards more complex technologies **(II)** and *path diversification* together with a re-orientation of the portfolio of similar complexity **(III)**. Furthermore, most of the technologies are relatively less complex, with all of the remaining technologies in the fourth complexity quartile and most of the new entries in the third.

The role of the technology life cycle as a mechanism of moving towards more complex green capabilities seems to be less important for Brussels; only Emergence technologies appear in the second complexity quartile, without any Diffusion or Maturity technologies. Also, unrelated diversification already appears to play a bigger role at all levels of complexity (partly driven by the very high relatedness of Y02P90/80).

While no new-to-the world technology is introduced, the three most complex new technologies still appear rather isolated in the technology space, constituting instances of *path emergence*: Y02D50/20, which is found in the Information and Communication Technologies Y02D cluster **(IV)**, which in Brussels is fairly limited as compared to Brittany, with only two more, also novel technologies and also largely without the non-green technologies; followed by Y02P10/10 for greenhouse gas emissions related to metal processing and by Y02W10/40, a technology related to wastewater treatment. But overall, no clear patterns emerge that could suggest mechanisms for green growth diversification pathways; this is also in line with the relatively small ranking improvement for Brussels from rank 114 in the first timeframe, to rank 90 in the second.

Over time, the clustering also for Brussels becomes more pronounced. In the **technology space at Y3 (Figure 15),** mainly two denser clusters appear: the first one is a relatively stable cluster at the core with fairly low complexity **(I)**, and the second one is the Information and Communication Technologies Y02D cluster **(II)** which seems to have been strengthened over time from the initial introduction in Y2, constituting a successful *path development* with entry into relatively complex Y02D technologies related to energy efficiency and reduction technologies Y02D10/20 and Y02D50/30 and new-to-the world Y02D30/20, as well as an adaptation technology related to infrastructures Y02A30/30. This *path development* is also coupled with a re-orientation of the technological portfolio with two exits.

For the dense core especially **(I)**, exits seem to be much less important, with almost all technologies at the fourth complexity quartile remaining in the technology portfolio and exits mainly occurring at the third complexity quartile; here however, the exited technologies are quite similar in terms of complexity to the entered ones, which suggests a *path diversification* rather than upgrading within the core at this timeframe.

Besides the Y02D technologies, one newly introduced technology at the top complexity quartile and west of the core **(III)**, is the wing lift efficiency technology Y02T50/30, which although very unrelated in the technology portfolio of Brussels (as measured by the relatedness density) seems closely related to the existing aeronautics weight reduction technology Y02T50/40; in terms of pathways this could potentially constitute a *path development* pattern. Similar to the previous timeframe, there are multiple instances of *path emergence* for instance to the south **(IV)**: Y04S50/10, an energy trading technology to the south or new-to the-world thermal building technology Y02B80/30 which are both unrelated and appear as isolates.

Figure 14: Brussels Technology Space (Y2)

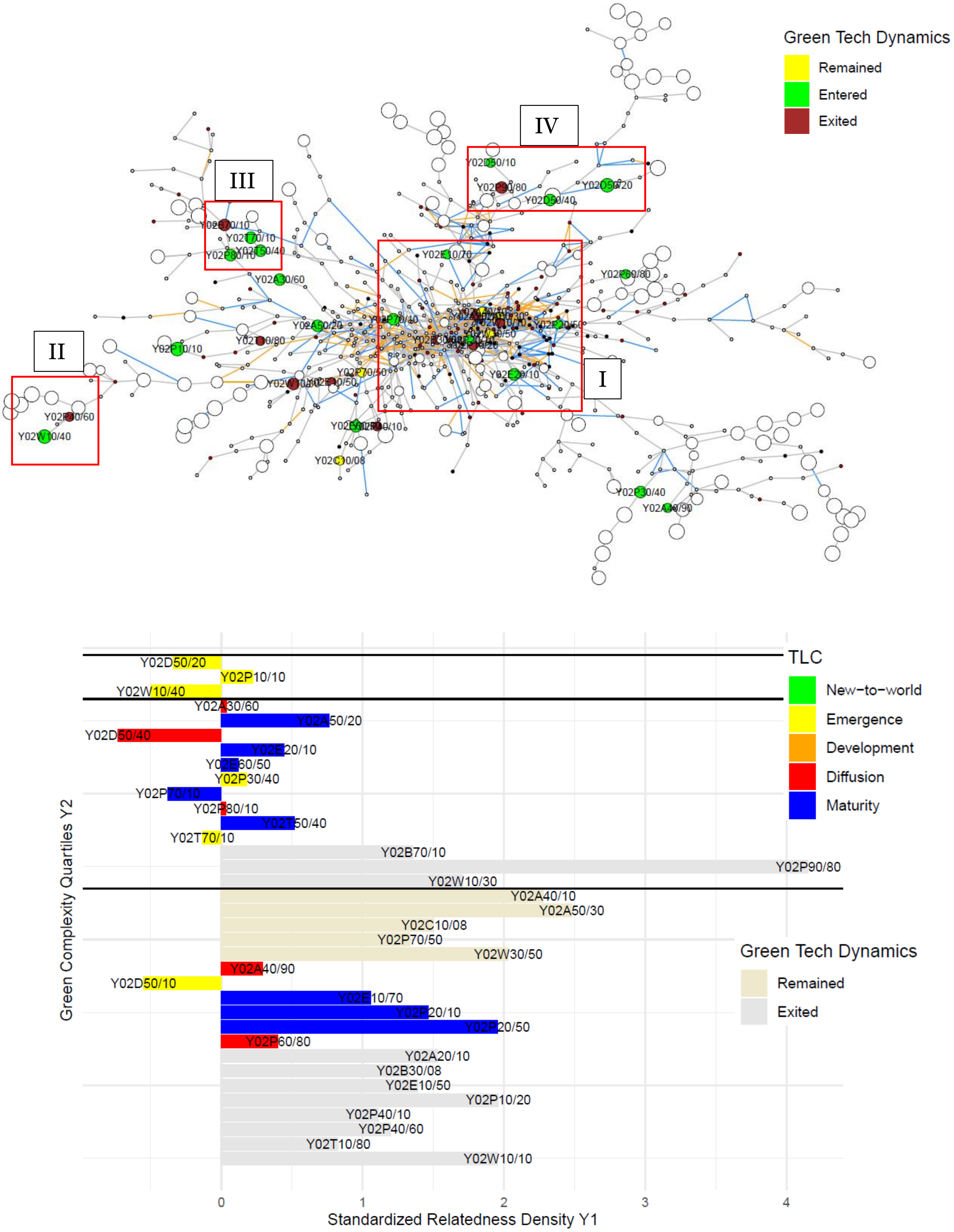
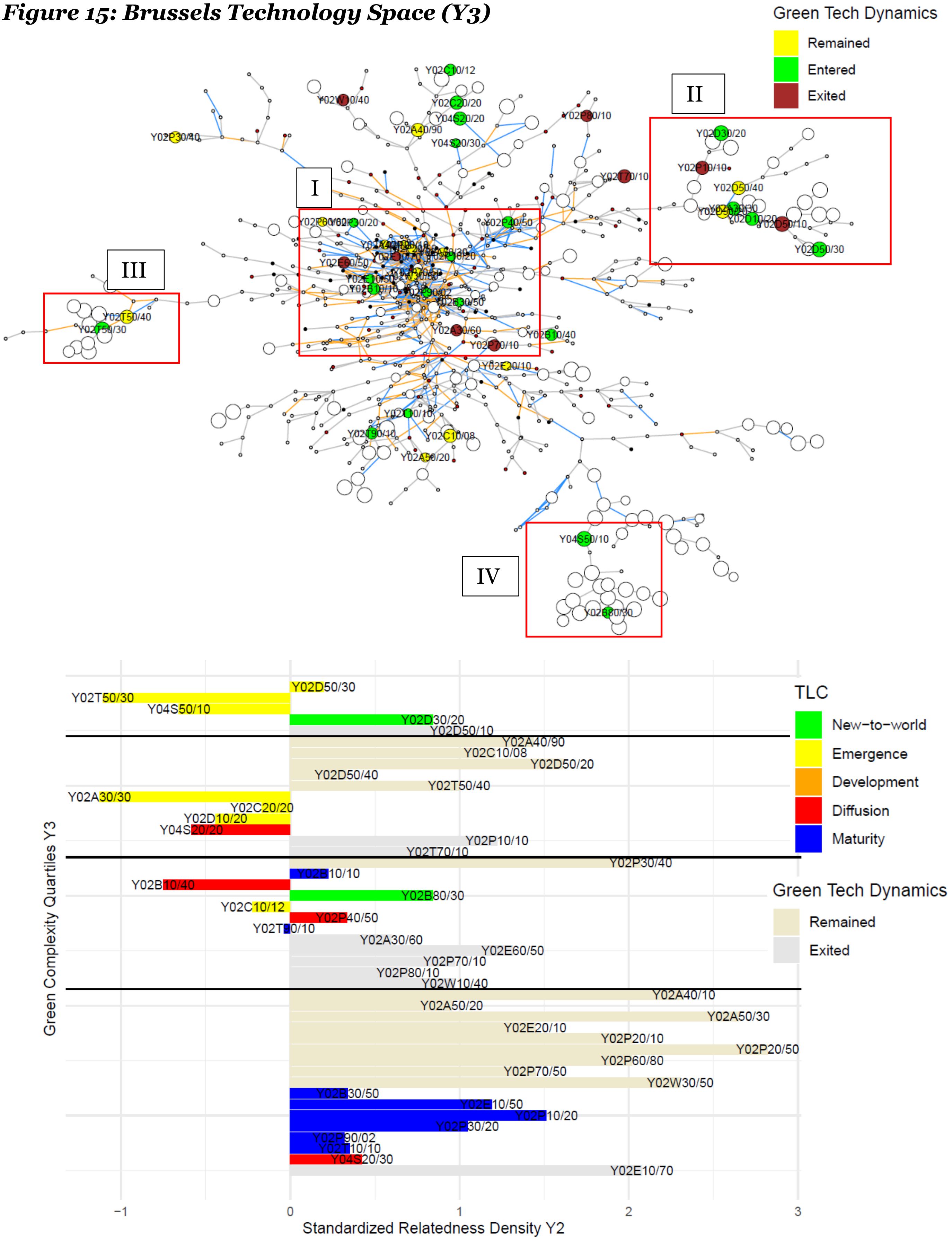


Figure 15: Brussels Technology Space (Y3)



While green growth pathways become more visible for Brussels the technology life cycle or the degree of relatedness do not appear to decisively influence these pathways; such that despite the high relatedness density at the core with a stable set of low-complex technologies, it appears that the region is not locked-in within this core and quite comfortably engages with fairly unrelated technologies also at the emergence stage of the technology life cycle.

As for **Brussel's technology space at Y4 (Figure 16)**, the dense, low-complex technological core largely remains **(I)**, albeit with some more newly entered green technologies at the diffusion and maturity stage, which are both more and less complex and are thus cases of both *path upgrading* and *path diversification*.

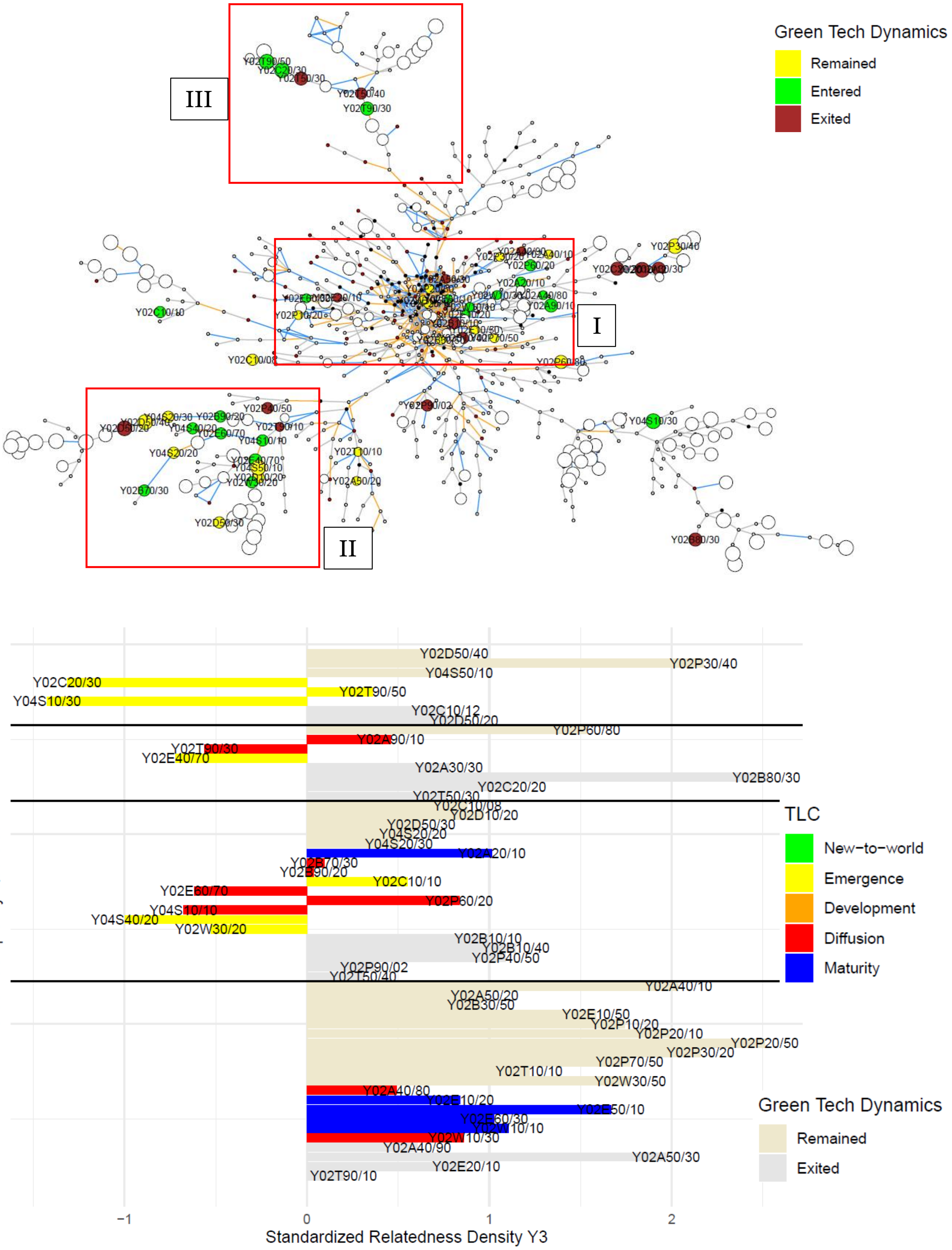
The prolific cluster related to Information and Communication Y02D to the south-west of the core **(II)** mainly exhibits entries, mostly at the third complexity quartile, constituting *path diversification*, but in this case mostly without a re-orientation of the portfolio, as the exited technologies are somewhat less close, and thus less related in the cluster. Despite their relative unrelatedness, i.e. of the systems integrating technology Y04S40/20 in the whole technology space of Brussels, the newly entered technologies are fairly well connected to some of the initially existing technologies.

Furthermore, to the north of the core **(III)**, one more, largely disconnected transportation cluster appears, containing two of the most complex newly entered technologies: fuel cell technology Y02T90/30 and an enabling technology to improve the mechanical performance i.e. aerodynamic of transport Y02T90/50. It appears that this is indeed yet another successful *path development* instance in the Brussels region as suggested before, as the technologies are fairly connected to the previously introduced aeronautics technologies Y02T50/30 and Y02T50/40. As those have also dropped to the second and third complexity quartile, their exit also constitutes a *path upgrading* instance in parallel to the *path development*.

Summary: Brussel's Green Growth Diversification Pathway

Brussel's pathway towards more complex green technologies is thus characterized by a mix of *path upgrading* and *path diversification* at the core, *path diversification* in the Y02D cluster, and most importantly, successful *path development* instances after an initial *path emergence*.

Figure 16: Brussels Technology Space (Y4)



Contrary to the initial dynamics in Y2, where no clear pathway mechanisms could be identified, the main driver of the eventual jump to rank 61 and 50, seems to be largely driven by those *path development* instances, which were responsible for establishing the Y02D cluster, as well as the eventual Y02T cluster.

On the other hand, the technology life cycle or degrees of relatedness seem to be much less influential in restricting or enabling the availability of green technologies, as more complex and largely unrelated technologies at the emergence stage were successfully added to the technology portfolio from the beginning.

Next to the eventual clusters, the core is fairly dense and stable over time, with exits playing a lesser role, especially at later timeframes. Importantly, also the dense core does not seem to prevent the emergence of new green capabilities at other parts of the technology space. At the green technology level, and again contrary than expected, enabling technologies played a comparatively little role for Brussel's green growth, similar to the engagement in new-to-the world technologies.

4.4.3 Lesser Poland Technology Spaces

Lesser Poland's technology space at Y3 (Figure 17) is primarily dominated by a dense core **(I)**, but also by substantial dynamics compared to the previous timeframe, with only two of the seven green technologies remaining and twelve being newly added. This would suggest an almost *radical renewal* pathway; this is at least partly true, besides the *path upgrading* in the core. Of particular interest, however, is the formation of a cluster **(II)**, around the high-complexity systems-integrating technology related to communication technology Y04S40/10, as well as an enabling technology related to power network operation and communication Y02E60/70, which were both already quite closely related to Lesser Poland's technology space at Y2. Furthermore, both technologies are already at the Diffusion stage, thus suggesting a possible inflow of knowledge developed outside the region as a mechanism towards obtaining more complex green capabilities. This potentially also allows for complex technologies in the same domain Y04S10/40 and Y04S10/10 at the emergence stage and unrelated within Lesser Poland's technology space, to be successfully added to this cluster. This suggests a very successful *path emergence* and (simultaneous) *path development* around technology domain Y04S.

To the east of the core **(III)** and to the west, three more or less isolated technologies appear, which are considered instances of *path emergence*.

Figure 17: Lesser Poland Technology Space (Y3)

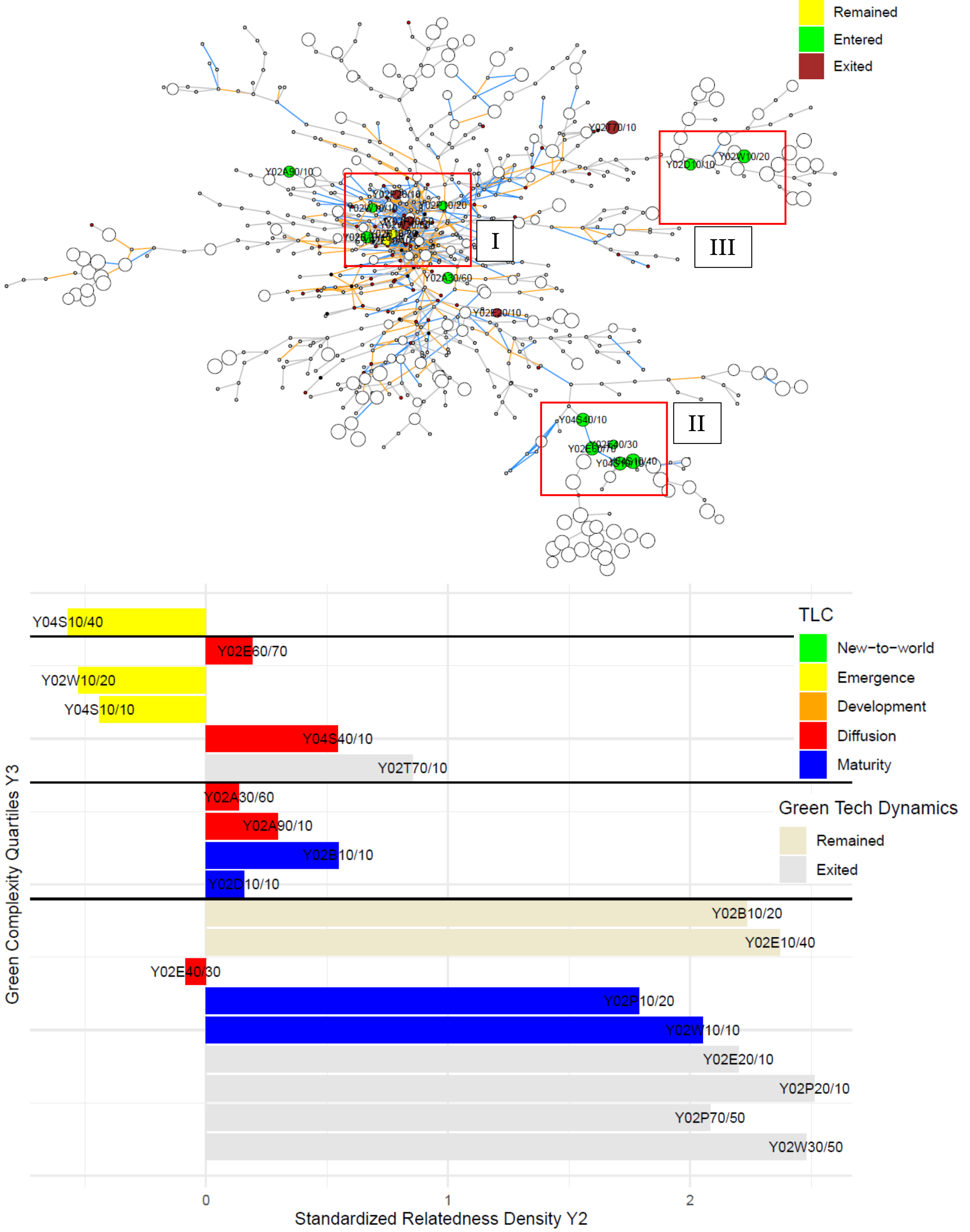
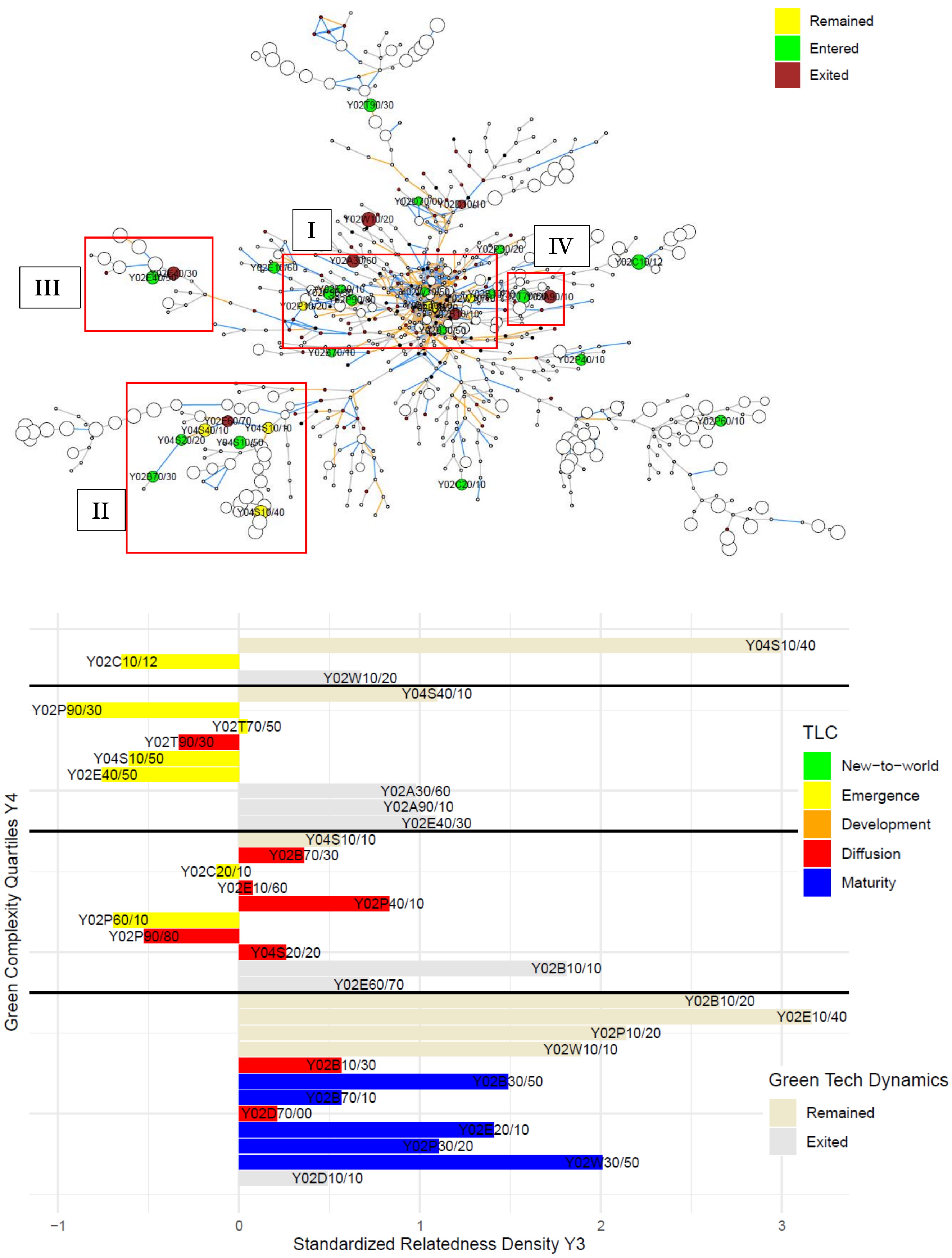


Figure 18: Lesser Poland Technology Space (Y4)



In particular, this concerns the ICT technology supporting adaptation to climate change Y02A90/10, as well as energy efficient computing Y02D10/10 in the third complexity quartile and sludge processing Y02W10/20 in the second.

In **Lesser Poland's technology space at Y4 (Figure 18)**, the core appears to be strengthened by newly added technologies **(I)**, which in this case are mostly instances of *path diversification* with a re-orientation of the portfolio, due to the lack of complexity substitution. Nonetheless, somewhat distant from the core, a relatively small low-complex sub-cluster appears around the process efficiency technology Y02P10/20 which was added in Y3 and now also contains two enabling process technologies Y02P90/30 and Y02P90/80 and a combustion technology Y02E20/10, thus constituting a successful *path development*.

Furthermore, parts of the cluster related to Information and Communication Y02D are visible to the south west **(II)**; while it is comparatively sparse and mostly consists of Y04S technologies, some *path diversification* within the cluster can be observed, such as towards Y04S10/50 at the second complexity quartile. In addition, there appear to be relatively many instances of *path emergence* scattered across the technology space in isolation, with the most complex being the CO_2 capture and storage technology Y02C10/12. As for these relatively complex technologies, only Y02T90/30 to the north of the core is in the Diffusion stage, and the energy efficiency technology Y02E40/50 to the west of the core **(III)** seems to be fairly related to the exited technology Y02E40/30. Beyond these cases, the mechanisms behind the appearance of those isolates cannot really be explained using this approach.

Connected to this is the question, whether Lesser Poland could leverage on the isolated *path emergence* technologies from the previous timeframe. While all these technologies are exited at this timeframe, rendering this endeavour largely unsuccessful, a case could be made for the ICT technology Y02A90/10 to the east of the core **(IV)**, which possibly enabled *path diversification* with re-orientation towards Y02T70/50, a technology related to maritime greenhouse gas emission reductions.

Summary: Lesser Poland's Green Growth Diversification Pathway

Lesser Poland's pathway towards more complex green technologies is thus characterized by a mix of *path upgrading* and *path diversification* at the core, considerable *path development* of and subsequent *path diversification* in the Y02D, or in this case, Y04S cluster and relatively scattered *path emergences* with however limited evidence of further, more complex *path development* (partly due to the limited timeframes).

Focusing on the mechanisms, the systems-integrating technologies Y04S might have been facilitated by the more mature life cycle stage, despite their comparatively high complexity and the coupling of more related with more unrelated branching opportunities allowing for simultaneous *path emergence* and *path development* at Y3. Nonetheless, for most of the other *path emergences,* no clear mechanism can be derived.

At the green technology level, the systems-integrating cluster Y04S could be viewed more as an enabling technology, while new-to-the world technologies do not play any role in Lesser Poland's green growth diversification pathway.

4.4.4 The green regional innovation capacity

Following the arguments that the creation of knowledge and development of industries, especially at higher complexity, is deeply embedded in routines, interpersonal contacts, local actor networks and the institutional contexts with substantial regional variety (Balland et al., 2019; Madsen & Hansen, 2018; Balland & Rigby, 2017), the observed pathways are reflected against the region's general innovation capacity. Although an exhaustive account is outside the scope of the chosen research approach, the results seem suggestive of both enabling and constraining functions for green growth.

For Brittany, the observed clustering of green technologies seems in line with its characterisation as a Medium-Tech manufacturing and service provider region with a strong industrial specialization (OECD, 2011b). While these clusters seem to mainly enable *path upgrading* and *path diversification* within those clusters, they also seem to constrain successful *path development* outside of these clusters. While this might also potentially be true for *path emergence*, Brittany seems to have been successfully enabling these by initially drawing on extra-regional knowledge with technologies at advanced life cycle stages, consistent with the pattern described by Grillitsch & Hansen (2019).

For Brussels as a knowledge-intensive capital region (OECD, 2011b), and consistent with the definition of a metropolitan region (Grillitsch & Hansen, 2019), all pathways seem attainable; in particular, multiple successful *path development* from initial *path emergence* instances could be observed. Potentially due to the comprehensive innovation support systems and the highly educated workforce, neither the technology life cycle nor the degrees of relatedness seem to be very influential in restricting or enabling the green growth diversification pathways; this is also in line with Xiao et al. (2018), who found that the effect of relatedness decreases with the increase of a region's general innovation capacity.

For Lesser Poland as a primary-sector intensive region with low-technology manufacturing (OECD, 2011b) and consistent with the definition of a peripheral region (Grillitsch & Hansen, 2019), the observations seem to somewhat deviate from the constrained innovation support system, as all green growth diversification pathways can be observed. While some *path emergence* and *path development* were driven by drawing on extra-regional knowledge with technologies at advanced life cycle stages, this was not the case for all instances for which no clear mechanism can be derived.

Taken together, the observed pathways are largely in line with what could be expected from the general innovation capacities, albeit with some nuances for the cases of Brittany, which could largely be explained and for Lesser Poland, which would require further investigation.

5 Conclusions

The transition towards the green economy, increasingly understood under the narrative of green growth as a way to reconcile economic growth and environmental benefits, requires structural economic changes. In particular, it requires capabilities that allow for handling of complex situations among economic actors, technological progress in the direction of green technologies and the identification of pathways according to different geographical contexts at the regional level (Capasso et al., 2019).

While the EEG literature provides some useful insights regarding the direction of technological change and regional economic development, in particular following the "principle of relatedness" (Balland et al., 2019) as well as methods to study the complexity of technologies and economies as a whole (Hidalgo & Hausmann, 2009), current approaches fall short in systematically accounting for the diversity of successful green growth diversification pathways and the underlying technological and regional factors associated with those. Insights into this variety, however, can help regions to better navigate their future green growth diversification pathways.

To fill this gap, a quantitative-exploratory research approach was proposed by combining the quantitative methods of EEG with the logic of the conceptual case-study approaches of the regional pathway literature, and applied to green technologies at the level of European regions. A particular focus was placed on catch-up regions, which were defined as those regions that have particularly successfully developed the required green capabilities.

In doing so, to examine and contextualize green growth at the regional level, the thesis posed two research questions, which are subsequently answered:

RQ1: Which European regions have successfully diversified into more complex green technological capabilities over time?

RQ2: What are the similarities and differences between catch-up regions with regards to their green growth diversification pathways in the technology space?

Regarding the first question, the green fitness ranking of European regions and its development over time were observed and two groups of regions identified: the European Green Fitness Leaders, as those with the highest rank position at the final period under investigation (2010-2014), and the European Green Fitness Catch-Ups, as those with the highest ranking improvements over time. To account for the regional dimension, Leaders and Catch-Ups were restricted to the respective top performers within the group of regions with similar innovation capacity.

This results in those regions, displayed in Table 16, which have successfully diversified into more complex green technological capabilities over time. In general, the Leaders have higher green patenting rates, more green technologies in which they possess competitive advantages and have a higher average green relatedness density than other regions with similar innovation capacity, thus confirming the general patterns of EEG also for regional green growth opportunities. On the other hand, it is possible to considerably improve the complexity of regional green capabilities over time, as evidenced by the Catch-Ups. These catch-up patterns can be largely divided into two groups: first, into those regions that have started to increasingly leverage on their latent green capabilities over time, as evidenced by their systematically higher average green relatedness density; and second, into those regions that have diversified into more complex green technological capabilities, despite a systematically lower average green relatedness density and thereby deviating from the principle of relatedness. The latter were also found to experience the highest ranking improvements, providing empirical evidence that such a strategy can be successful.

Table 16: Successful Green Fitness Regions in Europe

European Green Fitness Leaders		European Green Fitness Catch-Ups	
NUTS2	**Name**	**NUTS2**	**Name**
DE25	Middle Franconia	PL12	Masovia
FR10	Ile-de France	ES21	Basque Country
DE21	Upper Bavaria	FR52	Brittany
FR71	Rhone-Alpes	PL21	Lesser Poland
UKI	London	BE1	Brussels
ITC4	Lombardy	DK05	North Jutland
BE2	Flanders	AT12	Lower Austria
UKK	South West England	ITH4	Friuli Venezia Giulia
UKG	West Midlands England	ES51	Catalonia
UKD	North West England	ITC3	Liguria
DEA5	Arnsberg	ITH2	Trentino
FR52	Brittany	DE22	Lower Bavaria
ITC1	Piemonte	FR81	Languedoc-Roussillon
ITI4	Lazio	ITI1	Tuscany
PL12	Masovia	UKD	North West England
PL21	Lesser Poland	BE3	Wallonia
PL11	Lodz	FR43	Franche-Comte
		DE91	Braunschweig
		PL11	Lodz
		ES24	Aragon

In line with the second research question, those particularly successful catch-up regions were selected with differing general innovation capacity, to allow for a diversity of insights into possible pathways. These were Brittany (FR52) as a Medium-Tech, Brussels as a Capital and Lesser Poland (PL21) as a Primary-sector region.

The dynamics of entry, exit and remaining green technologies within the regional technology space were mapped out over time, to understand how those regions have navigated the technological dimensions of relatedness, complexity, and technology life cycle to explain the empirical patterns that have resulted in the considerable improvement of those regional green capabilities over time. To facilitate this explorative account, *path emergence, path development, path upgrading,* and *path diversification* were defined at the level of green technologies. Furthermore, explanations were proposed of how those technological dynamics might have been embedded with regards to the general innovation capacity.

Based on this, the main conclusions in terms of similarities and differences between catch-up regions with regards to their green growth diversification pathways in the technology space are derived as propositions, consistent with the exploratory nature of the research approach.

Proposition 1: Path upgrading, and path diversification are the most feasible green growth diversification pathways.

All three catch-up regions have successfully engaged in both these pathways, suggesting that they might be available to a broad range of regions with differing innovation capacities. For Lesser Poland, this somewhat deviates from Grillitsch & Hansen (2019) who did not account for the possibility of path diversification for peripheral regions, possibly also due to the focus on the level of industries. While Brittany has mainly engaged in path upgrading at the core of the technology space (and thus substituting technologies for more complex ones), Brussels and Lesser Poland used a mixed approach of path upgrading and path diversification there, possibly indicating a greater role of the technological core for regions with less distinct industrial specialization clusters. Within the existing clusters outside the core, all regions mainly engaged in path diversification, often coupled with a re-orientation of the technology portfolio, indicating the need to also consider strategic exits.

Proposition 2: Successful path development might either be facilitated by a dense core or constrained by dense clusters.

While all three regions have had instances of *path emergence*, only Brussels and Lesser Poland were successful in subsequent *path development*. While identifying the exact mechanism is outside the scope of the research approach, this could suggest that the industrial specializations within the dense clusters were prioritized by Brittany and path emergence technologies were therefore subsequently exited; a possible alternative explanation could be that a dense core is better suited to facilitate the flow of knowledge within the technology space, allowing for more isolated technologies to become more connected within the portfolio and subsequently benefit from additional inflows of ideas and innovation associated with this. These explanations would however require closer investigation.

Proposition 3: Pathways can become attainable by leveraging on technologies at advanced life-cycle stages.

This pathway mechanism was particularly important for Brittany but was also observed for Lesser Poland. As such, Brittany initially developed more complex capabilities by relying on entries into green technologies at the diffusion stage for path upgrading at the core, and thus profiting from extra-regional knowledge. Similarly, the simultaneous path emergence and path development around the Y04S cluster in Lesser Poland included technologies at more mature life cycle stages, despite their comparatively high complexity. On the other hand, life cycle stages did not seem to be a factor within Brussels, possibly due to the more comprehensive innovation support systems of a metropolitan region (Grillitsch & Hansen, 2019).

Proposition 4: More unrelated path diversification can be successfully coupled with more related path diversification in clusters.

Again, this pathway mechanism was observed for Brittany and Lesser Poland, but not for Brussels. For Brittany, this was observed in the Y02D cluster, where lower-complex, related technologies seem to have provided a steppingstone for high-complexity, unrelated technologies, particularly at the first timeframe, while the same was observed for Lesser Poland in the Y04S cluster. This points towards the potential of considering a coupled strategy for path diversification, in particular for regions that are not among the knowledge-intensive capitals or hub regions.

Proposition 5: Strategic exits provide room for green growth, also for path diversification and from initial path emergence.

Green technologies as studied here and elsewhere (Sbardella et al., 2018) are characterized by substantial dynamics within regional technology spaces, which could be explained by the high level of heterogeneity, complexity and uncertainty associated with them (Fusillo, 2020). Next to considering branching opportunities and new entries, this also underlines the role of strategic exits, in particular in cases of path diversification with re-orientation of the portfolio, without necessarily entering more complex green technologies per se, and also in cases of exited path emergences. These patterns were visible in all three regions and might have allowed them to access new knowledge sources more strategically, also when considering resource constraints at the regional level which might not allow for specializations in an unlimited number of technologies.

Proposition 6: Low-complexity technologies provide anchor points for green growth diversification pathways.

While green growth diversification pathways are mainly concerned with how to develop more complex capabilities, and despite the considerable exit dynamics, the lowest complexity quartile at the latest timeframe shows a much lower number of exits, in particular for Brussels and Lesser Poland, but also for Brittany. This could be suggestive of the need for green technology anchor points which decrease the overall volatility and uncertainty within the portfolio for successful green growth diversification pathways.

Overall, these propositions were considered as most applicable from the observed dynamics in the respective catch-up regions. Beyond these propositions, for instance in cases of path emergence, often no clear mechanism could be observed which would have explained the emergence of unrelated, complex isolates and was therefore left out.

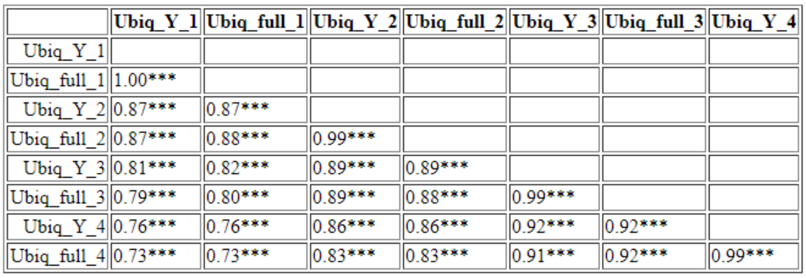
6 Discussion

6.1 Limitations of the research

As with any research approach, also the study here is not without its limitations. First, some methodological issues are presented, followed by some conceptual concerns. While an attempt was made to ensure construct validity of the research approach by deriving all utilized indicators from and anchored in previous research in EEG, some of the measures are not fully independent, mainly as they are based on the concepts of Revealed Comparative Advantages, using the Balassa-Index, and the associated ubiquity and diversity. In particular, this concerns the Fitness-Complexity algorithm on the subset of green technologies as proposed by Sbardella et al. (2018), the technological relatedness measure as proposed by Boschma et al., (2015) and following van den Berge et al. (2019) over both the subset of green technologies at the main group level and the full set of non-green technologies at the subclass level, as well as the technology life cycle measure as proposed by Barbieri et al. (2020). In doing so, complex technologies are generally also less related and mostly at the emergence phase. Nonetheless, as was for instance found in section 4.1.2, the fitness-complexity algorithm seems to successfully penalizes for technologies that are relatively less ubiquitous but are produced in low-fitness regions. Similarly, as the second dimension of the technology life cycle is the patenting intensity, this measure is not solely derived based on the ubiquity, and is also in line with other studies that have suggested that most green technologies are at an early stage of development (OECD, 2015).

A particular case of this concern, however, is that calculating the fitness on the subset of green technologies only and calculating the relatedness over the mixed set of green and non-green technologies, results in differences of whether a particular green technology is produced with RTA or not, as more fractional patent counts are included for the full set. For instance, the green fitness calculation for Brittany (FR52) is based on a diversity of 17 at the first timeframe, while the relatedness measure assigns only 12 green technologies which it produces with RTA. For the case of Lesser Poland (PL21) the diversity at the last timeframe is 27 and 28 respectively, while for Middle Franconia (DE25) the diversity is 60 and 73, respectively. While the tendencies are similar, also as evidenced by the Pearson Correlations in Table 17 and Table 18, in such a quantitative-exploratory setting in particular, those differences can impact the results considerably. Here, a pragmatic approach was taken to rely on the full set of technologies to only include those green specializations judged as specializations within the whole technology space, also as the relative impact of non-green technological specializations is considered an important factor (van den Berge et al., 2019) but similarly valid arguments could be derived for using the subset of green technologies only.

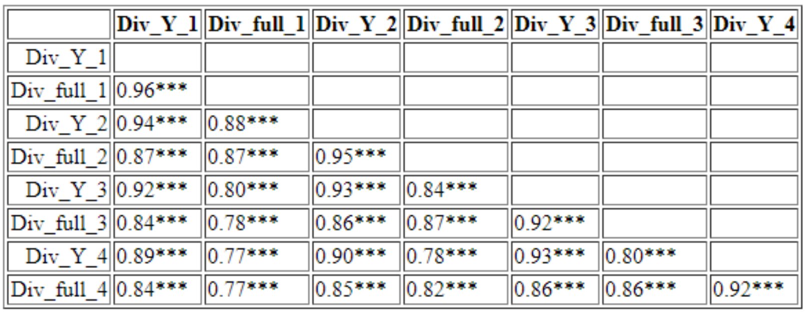
Table 17: Correlation between Ubiquity Full and Ubiquity Subset



	Ubiq_Y_1	Ubiq_full_1	Ubiq_Y_2	Ubiq_full_2	Ubiq_Y_3	Ubiq_full_3	Ubiq_Y_4
Ubiq_Y_1							
Ubiq_full_1	1.00***						
Ubiq_Y_2	0.87***	0.87***					
Ubiq_full_2	0.87***	0.88***	0.99***				
Ubiq_Y_3	0.81***	0.82***	0.89***	0.89***			
Ubiq_full_3	0.79***	0.80***	0.89***	0.88***	0.99***		
Ubiq_Y_4	0.76***	0.76***	0.86***	0.86***	0.92***	0.92***	
Ubiq_full_4	0.73***	0.73***	0.83***	0.83***	0.91***	0.92***	0.99***

****$p<0.01$; ** $p<0.05$; *$p<0.1$.*

Table 18: Correlation between Diversity Full and Diversity Subset



	Div_Y_1	Div_full_1	Div_Y_2	Div_full_2	Div_Y_3	Div_full_3	Div_Y_4
Div_Y_1							
Div_full_1	0.96***						
Div_Y_2	0.94***	0.88***					
Div_full_2	0.87***	0.87***	0.95***				
Div_Y_3	0.92***	0.80***	0.93***	0.84***			
Div_full_3	0.84***	0.78***	0.86***	0.87***	0.92***		
Div_Y_4	0.89***	0.77***	0.90***	0.78***	0.93***	0.80***	
Div_full_4	0.84***	0.77***	0.85***	0.82***	0.86***	0.86***	0.92***

****$p<0.01$; ** $p<0.05$; *$p<0.1$.*

A further limitation is the sole reliance on a data-driven approach to estimate the technological complexity and regional fitness. While this presents a relatively efficient way of considering the value of underlying, yet unobservable capabilities, and advancements such as the EFC (Tacchella et al., 2012) and the ECI+ (Albeaik et al., 2017) together with simulations (i.e. Mariani et al., 2015) have been used to improve the original method of the ECI (Hidalgo & Hausmann, 2009) itself, the resulting ordering of the complexity ranking would benefit from further expert evaluation. While it was mentioned in 3.3 that the resulting rankings are stable over time, suggesting a reliability of the measure, the validity of the measure as it concerns the accuracy of measuring complexity agnostically, also in the domain of green technologies cannot be fully ensured here.

A conceptual concern which is of particular importance here is the difficulty of fully differentiating between strategic decisions related to green growth diversification pathways on the one side, and simply unfolding processes on the other side. Thus, while the framing of path diversification, path emergence, path development and path upgrading is merely descriptive, the mechanisms behind those empirical patterns cannot be fully comprehended within this study setting. Thus, there might be a problem in turning empirical regularities into blueprints for other regions to follow, as was set out among the research aims. Connected to this, embedding the technological dynamics within the general innovation capacity requires more critical reflection and further, more concrete indicators to derive solid insights into mechanisms and influential factors for green growth. In line with this, the generalizability of the results is thus limited, and while the propositions were cautiously made and the catch-up regions carefully selected from the ranking and not pre-supposed, they might constitute special outlier cases with their respective green growth paths.

Nonetheless, the attempt made here, can be seen as a fruitful starting point for future research avenues. Before providing some suggestions, the theoretical implications of the research are discussed.

6.2 Theoretical Implications

This study has both complemented the existing literature related to the spatial formation of green capabilities and extended it with some contextual insights regarding the evolutionary processes that drive green growth diversification processes across technological and regional dimensions. In doing so it has contributed to the research agenda for green growth as set out by Capasso et al. (2019) by answering 1) which regional economies in Europe possess the capabilities to handle the complex and non-routines situations related to green growth, which were identified as the European

Green Fitness Leaders; 2) which regional economies in Europe have developed those green capabilities more successfully than others over time, which were identified as the European Green Fitness Catch-Ups; 3) which pathways those particularly successful European Green Fitness Catch-Ups have taken in directing their green technological progress; 4) how those pathways are enabled and constrained by the geographical context of those regions.

A first theoretical contribution is the systematic account of the regional level. Previous studies, in considering the green technological complexity and green economic complexity, have mostly relied on the country-level (Capasso et al., 2019; Mealy & Teytelboym, 2020; Sbardella et al., 2018; Fraccasia et al., 2018). This however disregards the substantial sub-national variety of green growth processes related to the creation of knowledge, development of industries and the institutional context which enables and constrains those processes (Grillitsch & Hansen, 2018; Madsen & Hansen, 2018). While the provided ranking itself is yet another testament to the difficulty of systematically increasing the complexity of the green portfolio, as most regions remain within the realm of their starting position in the fitness ranking, consistent with what was observed at the country level (Mealy & Teytelboym, 2020; Sbardella et al., 2018) and the general path-dependence of new green activities in an economy (Santoalha & Boschma, 2019; van den Berge et al., 2019; Montresor & Quatraro, 2019; van den Berge & Weterings, 2014), the regional view has also allowed to capture the uneven geographic distribution of those capabilities and identify notable nuances, such as the finding that the most successful catch-up regions in terms of ranking improvements were those, which were able to systematically outperform the relationship between the principle of relatedness, as measured by their comparatively low average green relatedness density.

A second contribution was made by proposing a quantitative-exploratory research approach. In doing so, an attempt was made to combine and bridge the well established methods in the quantitative literature in EEG (Balland et al., 2019; Boschma et al., 2015) with the language and logic of the more conceptual regional pathway literature (Grillitsch & Hansen, 2019; Isaksen & Trippl, 2014). This has facilitated the exploration of the technology space and has provided an idea of how those pathways, using notions of path emergence, path development, path upgrading, and path diversification could be explored for individual regions with regards to green growth opportunities. While a similar idea was previously proposed by Hamwey et al., (2013), they did not systematically account for the potential diversity of pathways and merely recommended to follow the principle of relatedness for green product development in Brazil. Furthermore, other explorative figures for the mapping of green technological opportunities, such as the Green Adjacent Possible by Mealy & Teytelboym (2020), with relatedness density on the x-axis, and technological complexity on the y-axis, similar to the smart specialization framework proposed by Balland et al. (2019), do not fully capture the relatedness between technologies in the technology space. This might prevent coupled (i.e. path diversification to both related and unrelated green technologies simultaneously within clusters), or subsequent branching opportunities if those linkages are not fully considered. In line with this, was the attempt to consider relatedness as a matter of degree rather than in a dichotomous way and highlighting both the relatedness in the technology space, as well as the (standardized) relatedness density as it pertains to the dynamics of entry, exit and remaining green technologies; as was argued by Whittle & Kogler (2020), overcoming this binary definition allows a shift in the discussion to understand how related or unrelated a new activity is to the existing knowledge base of the region.

A third contribution is seen in the derived propositions, as they shed light on the diversity of successful pathways, their associated mechanisms and contributing factors for green growth diversification. While path upgrading and path diversification were thus regularly observed for the Medium-Tech region of Brittany, as well as the Capital region of Brussels, also the Primary-sector intensive region of Lesser Poland was able to engage in both, which is not accounted for in the conceptualisation of Grillitsch & Hansen (2019). Furthermore, possibilities for path development seemingly differed and potential explanations were explored relating to dense cores as opposed to dense cores. On the other hand, two distinctive pathway mechanisms could be derived: first, relying on technologies at advanced life-cycle stages for new entries and thus profiting from extra-regional knowledge as well as the more standardized knowledge (Grillitsch & Hansen, 2019; Barbieri et al., 2020) and second, coupling more related path diversification with more unrelated path diversification in clusters; both mechanisms might potentially present steppingstones for non-knowledge intensive regions in particular. Contributing factors seem to be the consideration of strategic exits at the technology level beyond path upgrading, especially due to the high uncertainty of green technologies (Fusillo, 2020). While exits have been discussed in terms of their relatedness (Kogler et al., 2017; Boschma et al., 2014), this has not yet been done for green technologies and in terms of their complexity. Another contributing factor diametral to exits, seems to be the need to sustain a base of low-complexity technologies either at the core or within clusters, suggestive of decreasing overall uncertainty and allowing for path diversification.

While the propositions already point to considerable further research opportunities, a logical next step would be to investigate the three regions more closely using a case study approach and more systematically comparing the presence, quality and interaction of skills, physical resources, markets, institutions, and policies at the local and national scale as suggested by Capasso et al. (2019). This could certainly explain the observed pathways and mechanisms more thoroughly. Furthermore, as opposed to studying catch-up regions, an investigation into why other regions were not able to develop more complex green capabilities and identify potential blocking mechanisms is desirable.

A further research direction would be to estimate different degrees of relatedness more systematically as a driver of green growth. This could be done by following Coniglio et al. (2018), who constructed counterfactual distributions of relatedness in product spaces and assessed the degrees by estimating probabilities of non-random (related) entries as opposed to random (unrelated) entries; for Italian provinces they find that on average around 30% of new goods enter the basket that are largely unrelated to the existing products. It would be interesting to estimate whether and how this pattern is different for green technologies to derive better insights into further potential pathways.

6.3 Policy Implications

As for policy implications, the diversity of pathways along technological and regional dimensions, can be informative regarding future smart specialization strategies for green growth.

The conclusions drawn from this study seem to be reflective of the criticism that what constitutes “smart” in smart specialization, which is understood as expanding the capabilities through related technologies in the direction of more complex technologies (Balland et al., 2019), might prevent regions in developing their place-specific approach (Whittle & Kogler, 2020). While generalizability is limited, the three catch-up regions show empirical evidence that despite differences in the general innovation capacities, they were indeed able to deviate from this relationship and potentially benefit from the more complex green technology portfolio. To give concise policy recommendations however requires a better understanding of the driving mechanisms behind those pathways, which might have decreased the associated diversification risks.

For one, smart specialization strategies for green growth could focus not only on developing and expanding the knowledge core through related diversification opportunities towards complexity, but incentivise the inflow of extra-regional knowledge at advanced life-cycle stages for more complexity, which was an observed mechanism for Brittany and Lesser Poland. This might both enable subsequent pathways to become attainable within the region and potentially contribute to the knowledge base of the region by providing the described anchor points.

Secondly, smart specialization strategies should focus on a portfolio approach and for instance incentivize coupled branching opportunities within clusters to enable unrelated diversification, while simultaneously limiting the risk with related diversification. This is connected to the concern that policy interventions should be concerned with the additionality requirement and as such provide conditions for deviating from generally observed patterns (Frenken, 2016).

Furthermore, smart specialization strategies should be designed more according to the context and consider whether technologies are found more at the core of the technology space or within specialized clusters. This might influence the availability of potential pathways, in particular for path development outside of those dense clusters, which was largely unsuccessful in the case of Brittany. On the other hand, path upgrading and path diversification, possibly with a more strategic understanding of technological exits, seem fairly generalizable strategies that could also be part of smart specialization strategies for green growth.

Overall, contextualizing the “smartness” of smart specialization similarly according to technological and regional dimensions seems like a promising avenue for better policy design.

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8 Appendix I: EFC Formula

The EFC calculation is based on a non-linear, iterative equation that attributes lower complexity to the technologies patented by low-fitness regions as follows (Sbardella et al. 2018; with generalizations made by Mariani et al. 2015):

$$EFC = \begin{cases} \widetilde{F_r^{(n)}(\gamma)} = \sum_t M_{r,t} Q_t^{(n-1)} , \\ \widetilde{Q_t^{(n)}}(\gamma) = \left[\sum_t M_{r,t} \left(Q_t^{(n-1)} \right)^{-\gamma} \right]^{-\frac{1}{\gamma}} . \end{cases}$$

where scores are normalized after each step according to:

$$F_r^{(n)} = \frac{\widetilde{F_r^{(n)}}}{< F_r^{(n)} >}$$

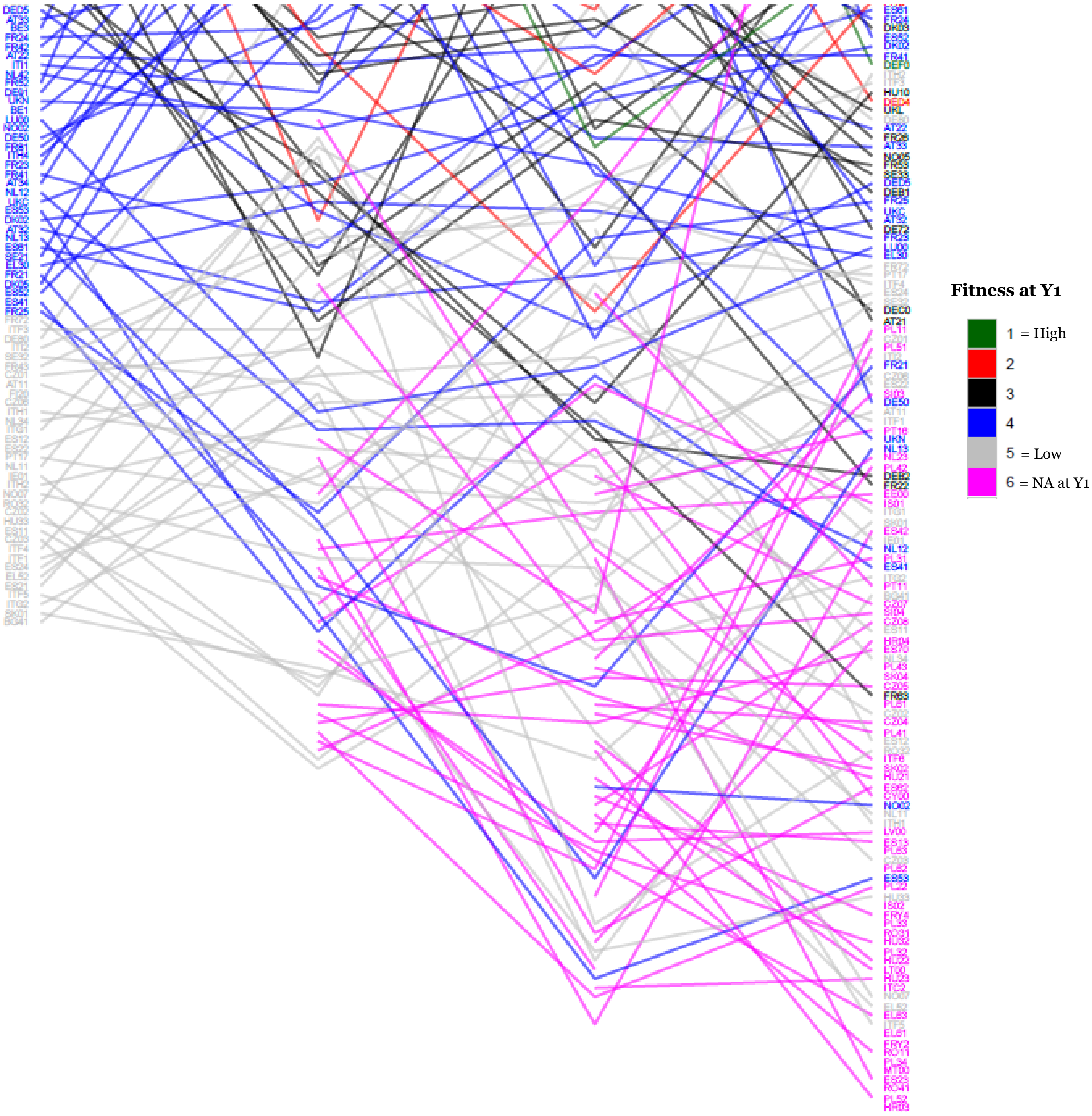
$$Q_t^{(n)} = \frac{\widetilde{Q_t^{(n)}}}{< Q_t^{(n)} >}$$

with the initial conditions:

$$F_r^{(0)} = 1 \quad and \quad Q_t^{(0)} = 1$$

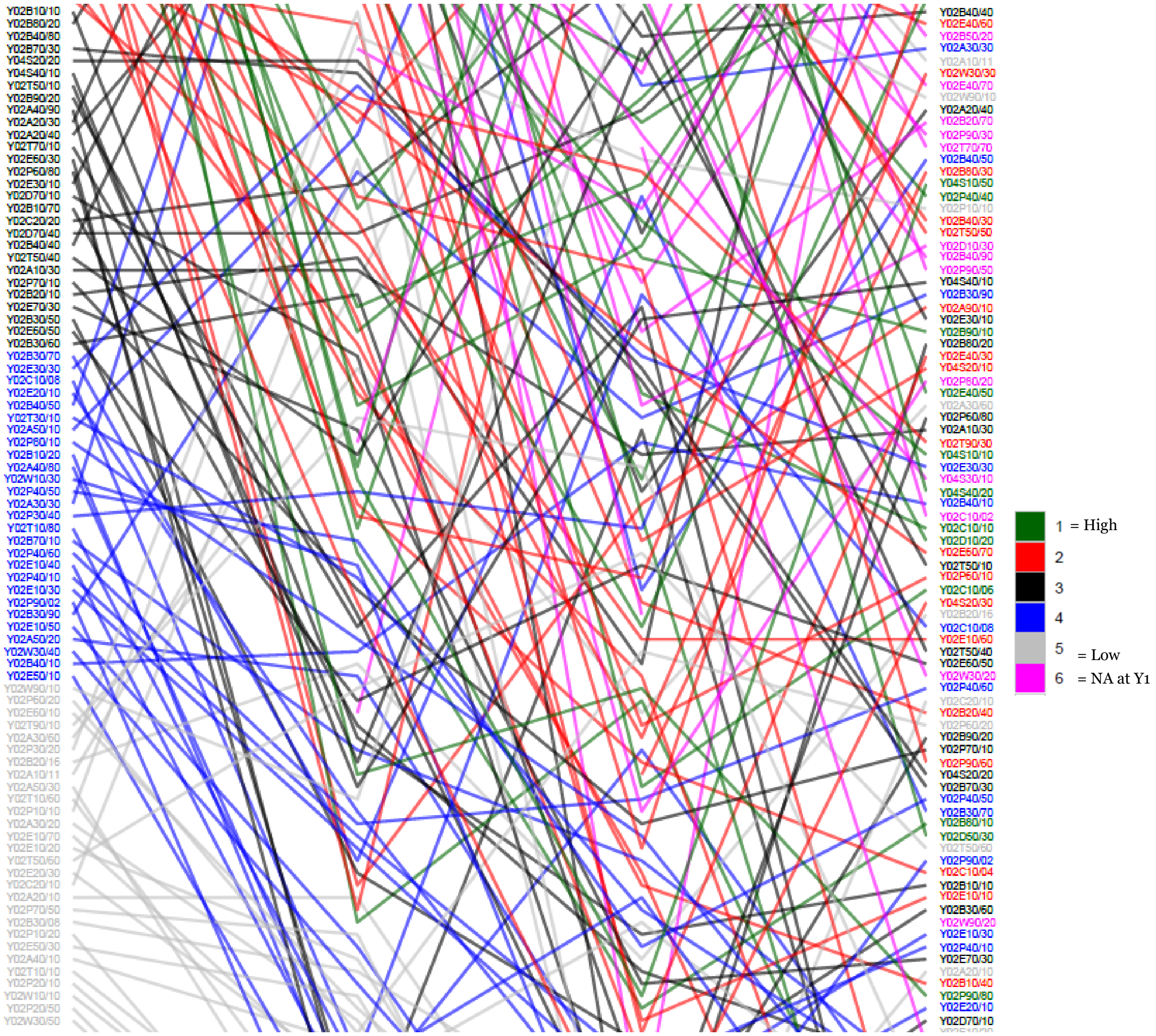
9 Appendix II: Low-fitness ranking regions

This figure provides an overview of the fitness ranking evolution for the lower end of the regions. Again, regions are color-coded according to their starting quintile in the first timeframe y=1 (1995-1999).



10 Appendix III: Middle-complexity ranking technologies

This figure provides an overview of the complexity ranking evolution for the middle part of the technology ranking. Again, technologies are color-coded according to their starting quintile in the first timeframe y=1 (1995-1999).



11 Appendix IV: Fitness Leaders & Fitness Catch-ups by Typology

These are the individual rankings of the best 10% of regions, alongside the median of the group and the lower 10% of regions. Regions were only considered in the final set of European Green Fitness Leaders or European Green Fitness Catch-Ups if they managed to be among the top 10% of regions in at least two of the rankings.

Ranking with Typology by Wintjes & Hollanders (2010)

	Regions Y1	Rank Y1	Regions Y4	Rank Y4	Regions Diff	Rank Diff
High-Tech (n=17)	DE21	2	DE25	1	DE91	-40
	DE25	3	DE21	3	SE23	-16
	NL41	23	DEB3	41	DE23	15
	SE23	65	DE26	81	DE14	43
	DE91	112	FI1D	102	DE71	46
Services (n=24)	FR10	1	FR10	2	BE1	-64
	SE11	4	UKI	5	DK05	-53
	NL33	46	BE1	50	UKJ	-1
	DK05	133	LU00	129	NL11	38
	NL11	153	NL11	191	DE30	44
Skilled Tech (n=39)	DEA5	11	ITC4	7	AT12	-49
	DEA1	13	DEA5	18	ITH4	-49
	ITC4	25	DE27	20	DE22	-43
	DEF0	29	ITC1	24	FR43	-41
	DEB1	85	ITI3	92	ITI3 AT11	3
	AT11	144	AT11	147	DEC0	56
	ITF1	163	ITF1	148	DED4	57
	SI03	171*	DEB2	154	DE94	68
	SI04	171*	SI04	169	DEF0	80
Absorbing (n=49)	FR71	10	FR71	4	ES21	-93
	UKG	18	BE2	8	FR52	-92
	FR82	21	UKK	10	ITC3	-47
	SE31	22	UKG	15	ES51	-47
	UKK	38	UKD	16	ITI1	-43
	FR22	100	NL21	97	IE02 FR24	-2
	ES22	151	NL12	162	ITH1	45
	IE01	154	NL34	174	FR26	46
	ES24	164	FR63	178	FR22	55

	ES21	166	ITH1	192	SE31	74
	ITC2	171*	ITC2	210	FR63	80
Public Knowledge (n=16)	DE40	14	ITI4	30	PL12	-125
	ITI4	73	PL12	46	ITH2	-45
	CZ01	143	DED5	122	BG41	-3
		171*		224*	DE40	84
Skilled Eastern (n=44)	CZ06	146	PL21	86	PL21	-85
	CZ02	158	PL11	138	PL11	-33
	HU33	159	PL51	140	PL51	-31
	CZ03	161	CZ06	143	PL42	-18
		171*	PL62	197	PL22	28
Southern (n=39)	ES53	125	ES61	103	ITF4	-29
	ES61	129	ES52	106	ES52	-28
	ES52	134	ITF3	111	ITF3	-27
	ES41	135	PT17	132	ES61	-26
		171*	EL52	212	EL61	44
		171*		224*	ES53	73

Ranking with Typology by OECD (2011b)

	Regions Y1	Rank Y1	Regions Y4	Rank Y4	Regions Diff	Rank Diff
Hub (n=30)	FR10	1	DE25	1	DE22	-43
	DE21	2	FR10	2	FR62	-34
	DE25	3	DE21	3	UKK	-28
	SE22	28	DE24	29	DE25	-2
	DE22	78	NL42	90	FI1D	38
	DE72	101	FI1D	102	DE14	43
	NL42	110	DE72	127	DE71	46
Capital (n=7)	DE30	9	UKI	5	BE1	-64
	AT13	48	DE30	53	CZ01	-4
	CZ01	143	DE50	146	DE30	44
Medium-Tech (n=55)	DEA2	8	FR71	4	ES21	-93
	FR71	10	BE2	8	FR52	-92
	DEA5	11	UKG	15	ITC3	-47
	DEA1	13	UKD	16	ES51	-47
	UKG	18	DEA5	18	UKD	-43
	DEB3	19	FR52	19	BE3 FR43	-41
	ES30	88	FR30	89	DEA5 FR82 DEA4 IE01	7

	FR72	137	ES22	144	FR22	55
	FR43	142	UKN	150	DEC0	56
	ES22	151	DEB2	154	DED4	57
	PT17	152	FR22	155	DE94	68
	IE01	154	IE01	161	DEF0	80
	ES21	166	FR63	178	FR63	80
Service (n=28)	SE31	22	NL32	31	DK05	-53
	NL32	40	UKM	42	SE21	-37
	NL33	44	NL33	45	DK02	-19
	NO04	91	NL21	97	DK03	10
	NO07	156	NO02	190	NO07	55
	SK01	169	NL11	191	SE31	74
	NL23	171*	NO07	211	NO02	74
Traditional (n=27)	ITC4	25	ITC4	7	AT12	-49
	ITH5	41	ITC1	24	ITH4	-49
	AT31	49	ITI4	30	ITI1	-47
	AT32	127	AT32	126	ITI2	1
		171*	ITH1	192	HU22	36
			CZ03	196	AT21	40
			HU22	207	ITH1	45
Inertia (n=34)	DE40	14	FR81	75	FR81	-43
	DEE0	76	DEE0	95	PL51	-31
	FR81	118	DE40	98	ES24	-30
	ITG2	168	ES11	171	DEE0	19
		171*		224*	ES53	73
					DE40	84
Primary (n=28)	HU33	159	PL12	46	PL12	-125
	EL52	165	PL21	86	PL21	-85
		171*	PL11	138	PL11	-33
		171*	EL52	212	EL63	42

Ranking with Classification by Regional Innovation Scoreboard 2014 (European Commission, 2014)

	Regions Y1	Rank Y1	Regions Y4	Rank Y4	Regions Diff	Rank Diff
Leader (n=34)	FR10	1	DE25	1	DE22	-43
	DE21	2	FR10	2	DE91	-40
	DE25	3	DE21	3	DK04	-18
	SE22	28	DEB3	41	FR10 DE21	1
	DE72	101	FI1D	102	DE14	43
	DE91	112	WQ	127	DE30	44
	LU00	115	LU00	129	DE71	46
Strong (n=95)	FR71	10	FR71	4	ES21	-93
	DEA5	11	UKI	5	FR52	-92
	DEA1	13	ITC4	7	BE1	-64
	DE40	14	BE2	8	DK05	-53
	UKG	18	UKK	10	AT12	-49
	FR82	21	FI1B	11	ITH4	-49
	SE31	22	UKG	15	UKD	-43
	ITC4	25	UKD	16	FR81	-43
	FI1B	26	DEA5	18	BE3	-41
	UKI	27	FR52	19	FR43	-41
	DK03	95	NL21	97	NL33 UKC	1
	NL34	148	EE00	156	FR83	53*
	ES22	151	SK01	159	FR22	55
	NL11	153	IE01	161	DEC0	56
	IE01	154	NL12	162	DED4	57
	ES21	166	SI04	169	DE94	68
	SK01	169	NL34	174	SE31	74
	NL23	171*	FR63	178	FI20	79
	EE00	171*	NL11	191	DEF0	80
	SI04	171*	FI20	224*	FR63	80
	FR83	171*	FR83	224*	DE40	84
Moderate (n=86)	NO03	45	ITI4	30	PL12	-125
	ITH3	67	ITC3	37	PL21	-85
	ITI4	73	ITH3	39	ITC3	-47
	HU10	82	ES51	43	ES51	-47
	ITC3	84	PL12	46	ITI1	-47
	ES30	88	ITI1	62	ITH2	-45
	ITI3	89	ES30	74	ITI4	-43
	ES51	90	NO04	82	PL51	-31

	NO04	91	NO03	85	ES24	-30
		171*	ES12	183	CY00	18
		171*		224*	NO07	55
					NO02	74
Modest (n=27)	ES53	125	PL11	138	PL11	-33
	BG41	170	PL31	163	PL31	-8
		171*	BG41	167	BG41	-3
		171*	PL52	222		53*
		171*		224*	ES53	73