CHAPTER 9

REGIONAL DIVERSIFICATION IN GREEN TECHNOLOGIES

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Abstract

A key intuition behind the European Green Deal is that the transition to climate neutrality should be growth enhancing. This will require massive changes in habits and laws, and, above all, an extraordinary effort in transforming technology, the most important determinant of pollution levels and economic growth. This chapter provides an overview of the current state and future outlook of green technologies across the European continent, through the lenses of the emerging paradigm of economic complexity. The analysis shows a heterogeneous landscape in Europe, in which specialization and diversification vary considerably, calling for different investment strategies at EU, national, and regional levels. The chapter highlights the importance of regional cohesion, and call for policies informed by the principle of accumulating capabilities: each region can look at its own set of skills and potential to direct investments towards technologies that are feasible, but also allow the region to accumulate new know-how and fuel growth.

1. Introduction

A key idea behind the European Green Deal is that the transition to climate neutrality should be growth enhancing. No one expects this to be an easy task: it will require massive changes in habits and laws, and, above all, it will require an extraordinary effort to transform our technology – the most important determinant of pollution levels and economic growth.

This chapter thus aims to give an overview of the current state of and future outlook for green technologies across Europe. It does so through the lens of the emerging paradigm of economic complexity, whose theoretical understanding of technology and empirical data-driven predictions are, in our view, very well positioned to contribute to this difficult discussion.

Chapter 2 of this report shows that the EU is still a technological powerhouse in green innovation. However, while this is true on the whole, there are some technological sub-classes in which Europe is not a global leader. Our analysis complements that of chapter 2 by studying key green technologies to identify potential gaps in this area in Europe. We use regional patent data to identify not only the differing abilities of regions in these key technologies but also the potential that regions have. That is the core empirical contribution of economic complexity: it can identify regions that are not currently actively developing a given technology (and, therefore, may not yet have acquired all the necessary capabilities) but have mastered related know-how and thus have the potential to develop the technology in the future. As we clarify in the following sections, we define know-how related to a target technology as the presence in a region of a set of technologies that are good predictors of its future development in that region.

We show that the landscape in Europe is heterogeneous, with regions with little or no green patenting and potential coexisting with regions with higher potential but few green patents and regions with high levels of green patenting and potential. We also observe that, while some regions are always high or low performing, for some, this varies depending on the technology.

This chapter does not exist in isolation. The body of literature investigating the link between economic complexity and sustainability has grown in recent years. Contributions have explored many directions of enquiry, ranging from measurement of the relationship between production and sustainability (e.g. Mealy and Teytelboym, 2022) to proposing indices of national or regional innovative performance (e.g. Pugliese and Tuebke, 2019) or development of methods to predict green innovation based on the composition of regional patent portfolios (Sbardella et al., 2022).[1] Irrespective of the question they tackle, researchers in the field share the view that, at regional scale, innovation (like economic development) is compatible with a process of accumulation of capabilities that makes possible increasingly complex outcomes. In this view, diversification and progress go hand in hand. It is, therefore, possible to extract valuable information about the future evolution of economic systems by measuring whether and to what extent their parts diversify over time.

In this chapter, we follow the literature that has been attempting to predict green innovation. With patent data, we observe how countries move from non-green to green technologies – and then apply that observation to European regions to assess which are better placed to develop green technologies in the future. To this end, we build

1 For a recent review of the literature applying economic complexity techniques to sustainability-related issues, see Caldarola et al. (2024).

on the methodology proposed by Pugliese et al. (2019) for identifying non-green technologies that are good predictors of the future appearance of a specific set of green technologies and use this information to compute a technology-specific regional-potential metric.

The chapter is organised as follows: section 2 introduces the reader to economic complexity. While we refer the reader to other more technical documents for an in-depth understanding, this section gives an idea of both the theoretical underpinning and the empirical methods of economic complexity. Section 3 identifies the EU's weaknesses in green technologies through a global comparison of 48 green technological categories. Section 4 presents the main results, mapping the green technology ability and potential of European regions. Section 5 discusses a possible key for reading the findings for policy purposes. Finally, section 6 concludes the chapter with some reflections.

2. Technology and complexity

Economic complexity is a set of methods with a strong data-driven component. With foundations in big-data analysis and machine learning, some see it as an entirely atheoretical method. However, economic complexity has deep theoretical roots, arising from an original understanding of what technology is. Technology, in fact, can be thought of as a combination three things (Balland et al., 2022):

- tools, like industrial machines – that is knowledge embodied as physical objects;
- codes, like blueprints or patents – that is knowledge codified into abstract symbols and stored in papers or computers;
- know-how – that is knowledge residing solely in the human brain.

Our ability to operate technology typically requires all three forms of knowledge, which complement each other. Imagine you come into possession of the blueprint for an electric engine: in order to make it operational you would need not only the material and tools to build it but also the know-how to do it successfully. Numerous empirical studies show that there is considerable tacit know-how involved in the operationalisation of a patented invention and that the subsequent transfer of technology is often achieved through personal relationships (Lee, 2012).

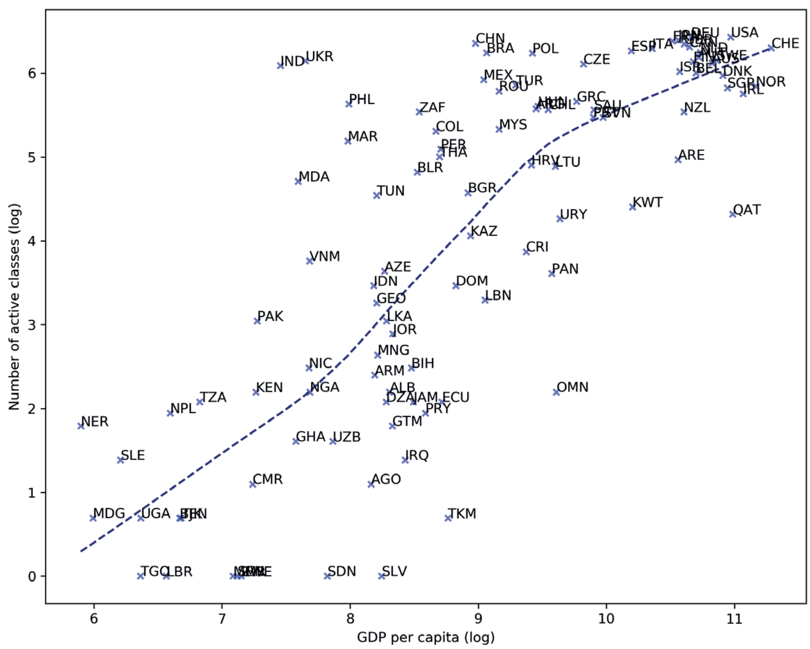
This observation highlights the fact that, among the three constituents of technology mentioned above, know-how is the real bottleneck: it cannot be easily bought, transported, transmitted or accumulated. Here is where the economic complexity approach conveys its important theoretical insight: given the limited capacity humans have to accumulate knowledge, technology can only accumulate at societal level through the distribution of know-how across different brains. But this implies that a society that has accumulated a lot of knowledge is a diversified society, with individuals who specialise in storing different bits of knowledge (Hausmann, 2013).

This theoretical insight resonates with a known empirical regularity about development: production in rich countries is more diversified than in developing economies. While it is subject to some nuances[2], this stylised fact appears to hold with respect to technological diversification (see figure 9-1).

2 There is evidence that, at a relatively high level of development, a country's production tends to reconcentrate. However, the reconcentration is only partial and, therefore, it still holds that, on average, production in rich countries is more diversified than in developing economies (Imbs and Wacziarg, 2003; Cadot et al., 2011).

Figure 9-1 gives a static depiction of the complexity theory of technology: developed countries have a lot of know-how, but since different parts of know-how are distributed across many brains, developed countries are more diversified on average. On the other hand, figure 1 also reflects the dynamics of knowledge creation in a complex world: invention often emerges from the combination of existing technologies (Fleming and Sorenson, 2001). Thus, a country that has a lot of know-how (that has access to many diverse types of know-how) has a higher chance of combining its bits of knowledge into new technology.

Figure 9-1 Technological diversification and GDP per capita



Note: The horizontal axis depicts the 2016 World Bank estimate of GDP per capita by country (in logs), while the vertical axis depicts the number of four-digit cooperative patent classification (CPC) patent classes in which the country was active in that year. Both axes are in logarithmic scale.

To maximise the transformative and growth-inducing effects of the European green deal, the EU should thus aim at mastering as many green technologies as possible. But how to achieve this? While economic complexity is not a magic wand that can formulate prescriptive policies, it can, nonetheless, offer guidance regarding the direction of policy intervention. The theory of economic complexity, in fact, suggests that, when technology is made by a combination of bits of know-how, it is possible that a country (or region) already has many of the necessary bits. The economic complexity methods known as 'relatedness' and 'product space' are designed specifically for that purpose: to allow us to infer which products or technologies are related to the know-how present in a given region.

In practical terms, this is achieved in three empirical steps.

1. Measuring the breadth of know-how of a country or region. By virtue of the complementarity between codes and know-how, patents can be used as a proxy for tacit know-how. Patents are also classified by technology, which gives an indication of which type of know-how is held in the territory. Figure 1 is an example of the measurement of know-how diversity via patents.

2. Measuring the similarity between technologies. To what extent do two technologies use the same bits of know-how? While it is very hard to give a direct answer, economic complexity proposes a method for indirect measurement: two technologies are similar if they are often produced in the same places. For instance, if most regions that produce innovations in four-stroke piston engines also produce a significant number of patents for two-stroke piston engines, we can deduce that the two technologies have many know-how elements in common.

3. Measuring the proximity of a place to a technology. Now that we have a map of which technologies require which types of know-how (from step 2), we can use the information on the existing know-how in a region or country (from step 1) to assess which technologies it is feasible for that region or country to develop.

From these three steps, we can assess whether a region has the know-how to make development of a given technology feasible, even if we do not currently see significant patenting activity. Throughout this chapter, we will call this measure the **potential** of the region in the technology.

3. Selection of green technologies

The prominent role of diversification in economic complexity theory suggests that the EU's focus should be on green technologies in which it is relatively weak. While the theory of (Ricardian) comparative advantages has at times been interpreted as indicating that one should focus, instead, on areas in which one is relatively strong, according to economic complexity, growth comes from the accumulation of diverse know-how. The challenge, therefore, is to fill technological gaps[3].

Since not all technologies are equally important, in this report we look only at green technologies that satisfy the following four criteria:

- the technology is sizable (worldwide patenting output above the median);
- the technology is growing (10-year worldwide patenting growth rate above zero);
- the EU's share is low (below that of the US or China);
- the EU is not closing the gap (the EU's growth is below that of the US or China).

To perform this assessment, we analyse green technologies in accordance with the CPC green patent classification[4]. Using an 8-digit system, this classification distinguishes between 48 green technologies. While it is possible to use economic complexity methods at higher or lower levels of aggregation, we believe the following level of coarse-graining is an excellent compromise: green technologies are

3 This is a multifaceted topic; see section 5 for a more in-depth policy discussion.
4 We consider the Y02 and Y04 patent classes.

considered in sufficient diversity to advance our understanding but not in so fine-grained a way as to introduce unwanted noise[5].

Applying the criteria above to the 48 green technologies, we select the following four.

- Filters (Y02A50/00): technologies for adaptation to climate change in human health protection, e.g. against extreme weather. They include catalytic converters to control or reduce vehicle emissions and technologies to guard against vector-borne diseases.
- Aeronautics (Y02T50/00): aeronautics or air transport. This includes drag reduction, wing-lift efficiency, weight reduction and efficient propulsion technologies for aircraft.
- Energy-efficient computing (Y02D10/00): climate change mitigation technologies in ICT – energy-efficient computing, e.g. low-power processors, power management or thermal management.
- Energy efficient communications (Y02D30/00): climate change mitigation technologies in ICT – reducing energy consumption in communication networks.

By using less strict criteria, a larger set of technologies could be analysed. However, we believe that limiting the number of technologies helps to keep the analysis focused. While future work could look at other innovative activities, in the next section, we analyse the possibilities for diversification in these four technologies.

4. Main results

To assess the potential of different regions in the EU with respect to these four technologies, in which the EU is lagging, we use the three-step methodology outlined in section 2. In the context of green technologies, the steps are as follows:

- measurement of the capacities of EU regions in all technologies (not solely green technologies);
- measurement of the relatedness between non-green and green technologies (using global data);
- computing of a measure of potential: does the region have non-green technologies that are related to the green technology of interest?

This approach is very suitable for evaluating potential in regions where there is no output. As discussed in section 2, economic complexity has both a theoretical and an empirical basis. The driving principle behind the method can be found in both. The theoretical basis suggests the use of information on a region's existing know-how (together with a map of similar technologies as regards required know-how) to assess whether a technology has potential in that region. However, from an empirical perspective, we are often not in a position to judge whether two technologies require similar know-how. That is why similarity between technologies is assessed via methods resembling machine learning techniques.

5 We also note here that the methodology is flexible and can accommodate a variety of technological definitions. In chapter 2 of this report, for instance, the methods of economic complexity are employed to study 15 key strategic technologies, including (but not limited to) green technologies at a different level of aggregation.

When we buy a pillow online, we may be prompted to buy a pillowcase as well. Such recommendations are not based on knowledge of the relationship between the two objects but on other people's purchasing habits: if many users have bought pillows and pillow-cases together, an online platform may infer a connection and make a recommendation. In a similar way, if many countries are innovating in a given pair of technologies, one may infer a technological similarity between them.

This was the original intuition of Hidalgo et al. (2007). Since then, extensive evidence has been accumulated showing that the appearance of products and technologies can be predicted (Hidalgo et al., 2018). We internally validate the exercise in this analysis by verifying that our measure of green-technology potential can correctly predict the appearance of a green technology in the following 10 years.

While patenting output in the four green technologies is low, it is not zero in all regions in Europe. It is, therefore, useful to see in which regions patenting activities in these areas have already taken place. For every region, our analysis highlights both the patenting activities and the potential for patenting in these green technologies – a potential that we assess via the economic complexity methodology.

We summarise our core results in the maps in figures from 9-2 to 9-5. The maps depict the actual patenting activities through changes in hue: oranges for regions with few patents, purples for medium-level patenting and blues for the regions most active in the technology. Potential is highlighted by saturation. For instance, regions with most patenting will have the following colours: light blue for low potential, mid-toned blue for medium potential, darker blue for high potential. The full colour scheme can be seen in the top-right corner of each map.

If one looks at the colour pattern of all of the maps together, one feature stands out: there is an almost complete absence of light pink and light blue. This implies that, when significant patenting activity in a technology occurs in a region, our measure of potential correctly assigns a high value to that region[6]. The opposite is not true: the prevalence of yellow and orange suggests that there are many regions with high potential and low levels of patenting activity, indicating the absence of specific capabilities but the presence of related know-how. These regions could be a good starting point for policy purposes. In section 5, we discuss in more depth possible interpretations of these patterns for policies at regional level. Hereafter, we describe the findings in a more neutral manner[7].

A second common feature of the maps is that some core regions – partially along Europe's blue banana but especially in southern Germany and southern France and the Île-de-France – perform highly in almost all technologies, while others – specifically in eastern Member States and, to a lesser extent, the Iberian Peninsula – are often characterised by a lack of both patenting and potential.

In spite of this, a third feature that stands out is the variety across the maps, with some regions having high capabilities or high potential in some technologies, while performing poorly in others.

Figure 9-2 summarises our findings concerning regional[8] innovation in green technology Y02A50/00 (a class that includes catalytic

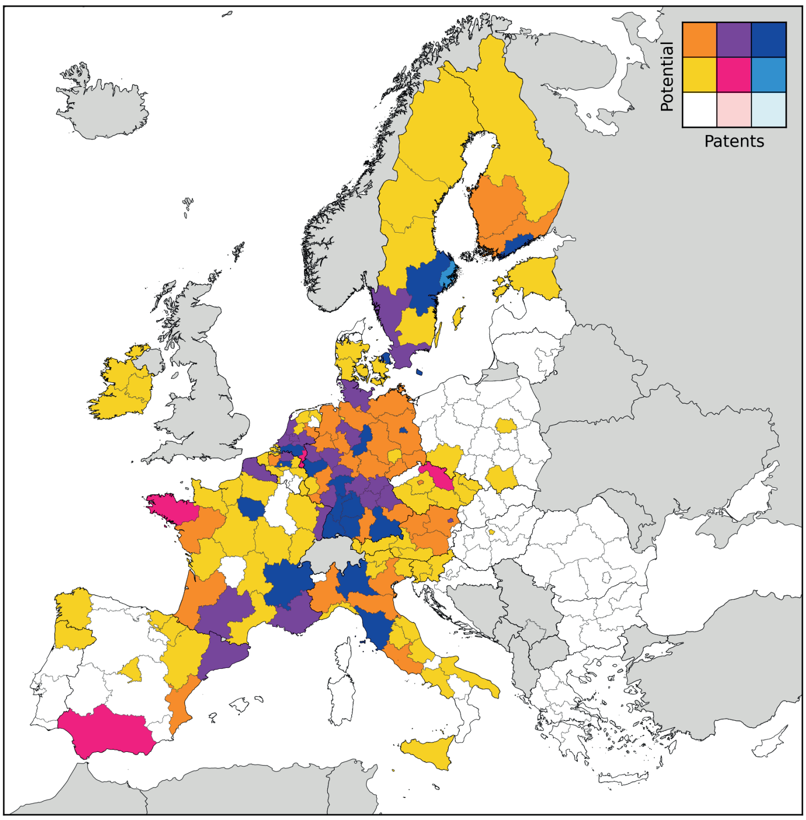
6 Note that our measure of potential does not use information on patenting in green technology. This suggests that potential is an early sign of future patenting. We see this as a corroboration of our approach: the potential metric we propose is likely capturing a relevant signal.

7 Some would say the analysis in this section is 'positive', while that in the following section is 'normative'.

8 NUTS 2 regions as defined by the 2021 nomenclature of territorial units for statistics.

converters for vehicle emission control or reduction, which, for simplicity, we label as 'filters'). The map shows a heterogeneous landscape across the EU, with low levels of patenting and potential (white) in many regions. Such regions are concentrated mostly in eastern Member States and the Iberian Peninsula. The remaining Member States are mostly coloured, which implies that their regions have at least medium patenting potential in filters, irrespective of the volume of patents they currently produce. Most of the coloured regions are either yellow or orange, meaning they have medium or high potential and low current levels of patenting. Regions of this kind are present in all Member States active in green technology. The map also shows a relatively large number of violet and dark blue regions, i.e. regions that combine high potential with medium or high patenting activity. Purple regions are concentrated mostly in France, Germany and Sweden, while blue regions also appear in Belgium, Denmark, Finland, Italy and the Netherlands. A rare occurrence in figure 9-2 are pink regions, i.e. regions with medium potential and medium patenting activity; we see a few in Czechia, France and Spain. Less frequent still are medium-toned blue regions, i.e. regions with medium potential and high patenting activity; we see only one such region, in Sweden.

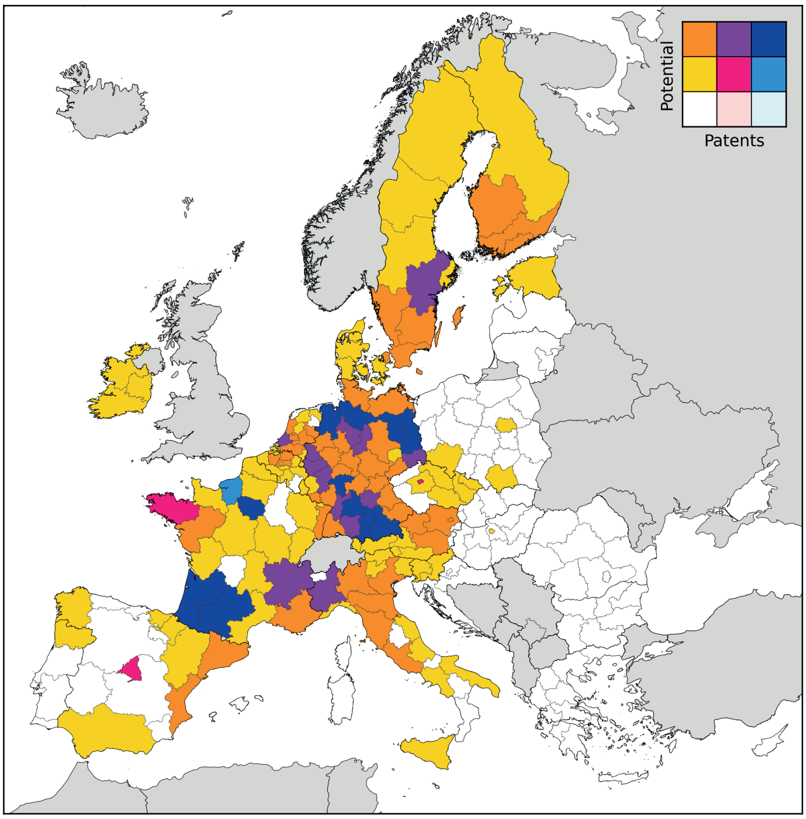
Figure 9-2 Map for green technology 'filters'



Note: The map depicts the level of patenting activity in and the potential for green technology Y02A50/00 – technologies for adaptation to climate change in human health protection, e.g. against extreme weather ('filters'). Each NUTS 2 region is assigned a colour based on two variables: number of patents determines the hue (low: oranges, medium: purples, high: blues); potential of the technology determines the saturation (low: white, light pink, light blue; medium: yellow, pink, medium blue; high: orange, purple, blue).

Figure 9-3 depicts activity in green technology Y02T50/00 (aeronautics). The prevalence of yellow and orange tones indicates that there are many regions with potential in this technology. With minor differences compared with filters, a lack of patenting and potential in aeronautics is again observed in the Iberian Peninsula and across the east of the EU. Additionally, highly performing regions in France and Germany maintain a relatively strong position. However, compared to filters, there are important differences. For instance, the good performance (highlighted in blue) of regions in south-western France and northern Germany is noteworthy – likely driven, in part, by the presence of Airbus. Beyond France and Germany, a few purple regions (strong potential, medium-level patenting) are observed in Italy, the Netherlands and Sweden, while pink (medium-level potential and patenting) can be found in Madrid, Brittany and Prague. Again, there is only one region in light blue (medium-level potential and high patenting), namely Upper Normandy.

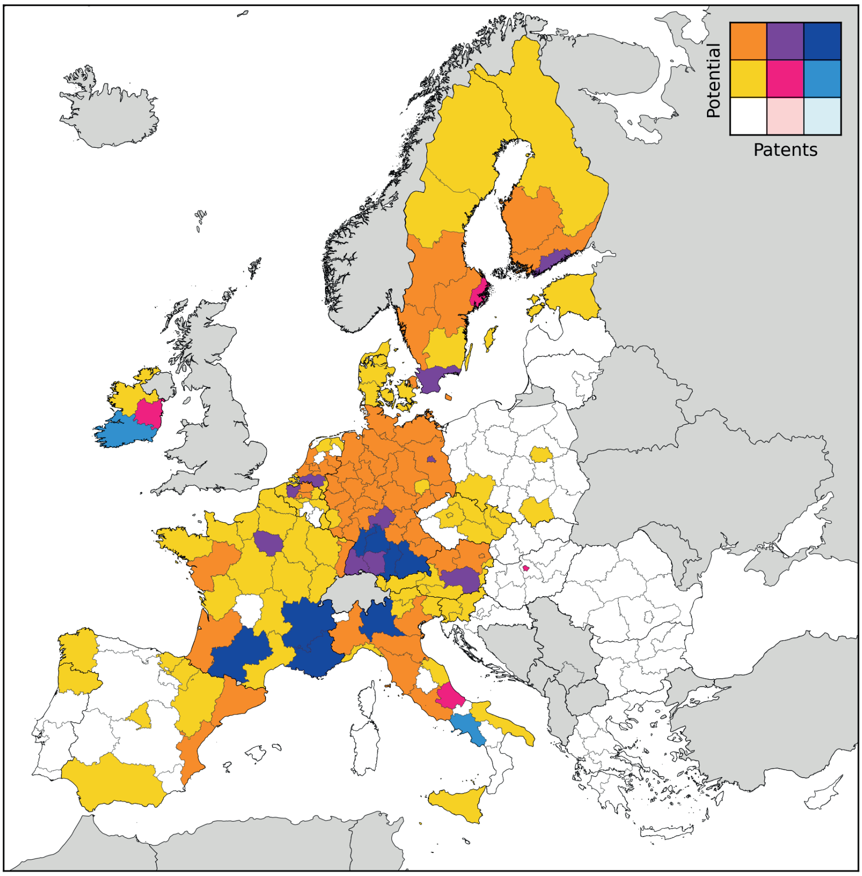
Figure 9-3 Map for green technology 'aeronautics'



Note: The map depicts the level of patenting activity in and the potential for green technology Y02T50/00 – aeronautics or air transport ('aeronautics'). Each NUTS 2 region is assigned a colour based on two variables: number of patents determines the hue (low: oranges, medium: purples, high: blues); potential in the technology determines the saturation (low: white, light pink, light blue; medium: yellow, pink, medium blue; high: orange, purple, blue).

For the green technology, energy-efficient computing (figure 9-4), we can identify the usual broad patterns. Nonetheless, there are some important differences. Northern Germany is not as strong as in the other three technologies analysed. There are only a few high performing (blue) regions, mainly clustered around the Alps in France, Germany and Italy (the only exception being the region of Midi-Pyrénées in France). We observe promising potential in purple regions in Austria, Belgium, Finland, France, Germany, the Netherlands and Sweden and medium potential with significant patenting activity (pink and light blue regions) in Hungary, Ireland, Italy and Sweden.

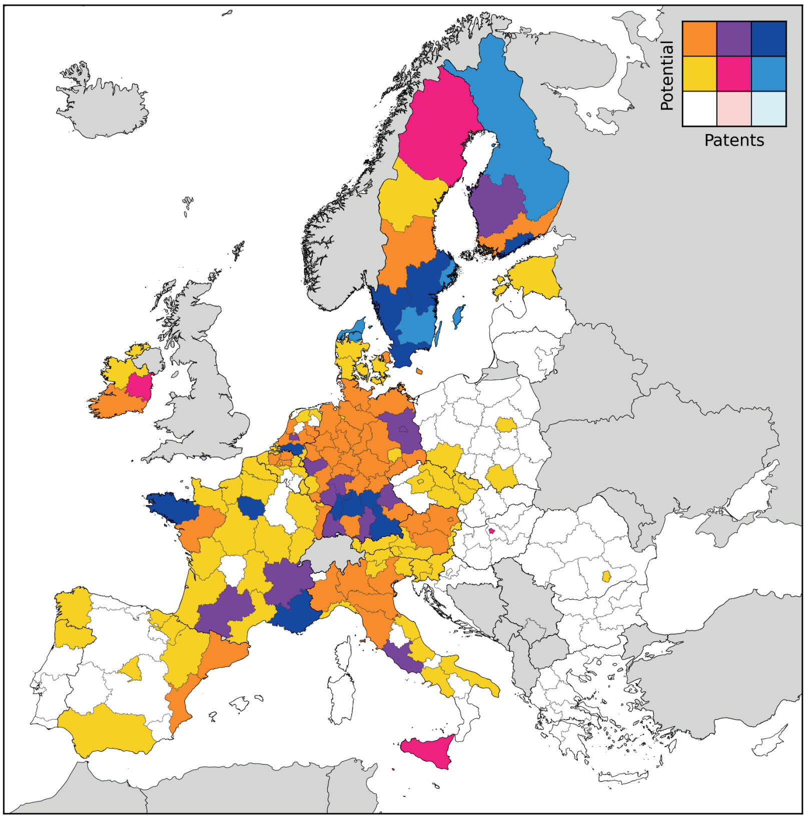
Figure 9-4 Map for green technology 'energy-efficient computing'



Note: The map depicts the level of patenting activity in and the potential for green technology Y02D10/00 – climate change mitigation technologies in ICT: energy-efficient computing ('energy-efficient computing'). Each NUTS 2 region is assigned a colour based on two variables: number of patents determines the hue (low: oranges, medium: purples, high: blues); potential in the technology determines the saturation (low: white, light pink, light blue; medium: yellow, pink, medium blue; high: orange, purple, blue).

Lastly, figure 9-5 highlights regional performance in energy-efficient communications. Beyond the patterns that are common across the maps, the most striking feature is the strong performance of Finland, Sweden and (to a lesser extent) Denmark. Regional hubs in this technology also exist in Belgium and, as usual, France and Germany. Other areas of interest are the region of Lazio, which is purple, and the mid-performing regions of Budapest, Eastern and Midland Ireland and Sicily.

Figure 9-5 Map for green technology 'energy-efficient communications'



Note: The map depicts the level of patenting activity in and the potential for green technology Y02D30/00 – climate change mitigation technologies in ICT: reducing energy consumption in communication networks ('energy-efficient communications'). Each NUTS 2 region is assigned a colour based on two variables: number of patents determines the hue (low: oranges, medium: purples, high: blues); potential in the technology determines the saturation (low: white, light pink, light blue; medium: yellow, pink, medium blue; high: orange, purple, blue).

5. Policy

In this chapter, we have aimed to highlight that (green) technological diversification is important for growth. For this reason, we have focused our analysis on four technologies where the EU, by some measures, has been performing poorly.

The idea of focusing on 'weak' technologies is justified by the economic complexity theory of growth, but to avoid misinterpretation we feel it is necessary to better explain the concept with a few remarks.

Firstly, focusing on weak technologies does not mean neglecting one's comparative advantage. The guiding principle, in this context, is that of accumulating capabilities. Thus, policies may focus on technologies that are closely related to currently available know-how but are not yet fully developed. This is similar in spirit to the entrepreneurial discovery process in smart specialisation, where the aim is to focus on one's own competences and capabilities in order to expand into new domains. Regions that are coloured yellow and orange in section 4 are prime candidates for this type of policy. Such policies may also be suitable for purple and pink regions, which already have some patenting activity to show for. Blue regions, on the other hand, have significant patenting in the technology, though that does not necessarily mean that public investment in those regions would go against the principles of economic complexity. This relates to our second remark.

Specialisation and diversification are often a matter of scale. We have observed that wealthier countries are more technologically diversified, but that does not imply that this translates to lower levels, for instance to cities or regions. Some technologies may need agglomeration economies and, while at national level diversification may be desirable, at subnational level it may make sense to concentrate on just a few areas. This is perhaps the case when a country is relatively weak in a technology but has a region that exhibits some capabilities in that technology. The concept also translates to a larger scale, for instance EU level: when assessing how to address low levels of performance in a technology, the decision on whether to invest more in regions with high potential or in regions with high capability might take into account the degree of concentration in the technology.

Thirdly, the guiding principle of accumulation of capabilities can also inform policies from a regional cohesion perspective. In other words, while the maps show some variety, a number of regions (and countries in some cases) have little patenting activity and little potential. A separate analysis could find out which green technologies are most closely related to currently available know-how in these regions, giving them an opportunity to contribute to the green transition, while accumulating capabilities (and growing) in the process.

6. Conclusions

In this chapter, we have applied the worldview and methods of economic complexity to the issue of the achievement of a growth-inducing green transition. The theory of economic complexity states that growth happens through the accumulation of a diverse set of capabilities, indicating that the EU should attempt to master a variety of green technologies rather than focusing on what it does best. But how can this be achieved?

Economic complexity gives an indication of how the EU can accumulate such capabilities. Technological diversification of countries and regions rarely happens in big leaps. Rather, it is a gradual process, with countries and regions gravitating towards new technologies that are, to some extent, similar to those that they have already mastered.

This chapter has thus performed an empirical assessment of the diversification possibilities of European regions – that is, their potential in a specific green technology, based on current capabilities. We have identified four green technological classes that appear important from observation of worldwide patenting activity and in which the EU seems to be lagging behind China and the US. For these four technologies, we have looked at existing capacity and potential across the EU, identifying which regions are always strong, which often underperform, and which have capabilities geared towards a specific technology but not towards others.

We believe this analysis can provide a rich framework for designing policies at different scales. At EU and national levels, officials who are interested in a specific technology can use the framework to help identify investment opportunities. Regions that are already strong are potentially good candidates if the technology of interest exhibits strong local externalities and clustering behaviour. On the other hand, when these externalities are not present to any great extent, policy interventions could target regions with high potential.

For regional policymakers, the framework can provide guidance as to which technologies are worth focusing on. The guiding principle, we argue, should be that of accumulation of capabilities: each region should look at its own skill set, as well as its potential, and only invest in technologies that are feasible to develop and that will allow the region to accumulate new know-how that fuels growth.

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