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EDITORIAL

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Unseen costs: the inequities of the geography of innovation

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1. INTRODUCTION

Regional studies scholars have long had a keen interest in studying innovation, viewing it as the main driver of regional economic growth and development (Asheim & Gertler, 2005; Audretsch & Feldman, 1996). Technological innovation boosts firms' productivity, industries' international competitiveness, digital and green transitions, and the overall economic performance of national and local economic systems. As a result, it is no surprise that the question of how to make regions more innovative has been among the most important research questions in this literature over the last three decades. The opening up of regions to external networks and the strengthening of their technological and innovative capabilities have largely been the mantras of most such literature and related policy recommendations (e.g., Bathelt et al., 2004; Giuliani & Bell, 2005; McCann & Ortega-Argilés, 2013; Tödtling & Trippl, 2005). This research has also constituted the foundation for regional innovation policies, whose underlying rationale has so far predominantly been to foster the creation and diffusion of innovation (e.g., Barca, 2009; Foray, 2014). Research in both regional studies and other fields has vivisected the topic of economic growth and regional development, focusing on what is most needed: first, and above all, more innovation, but also more entrepreneurs, spinoffs, venture capitalists, global knowledge networks and value chains, skills and capabilities, markets, talents and training, multinational enterprises (MNEs), related and unrelated variety, complexity, etc. (Audretsch et al., 2006; Balland et al., 2019).

The broad consensus on the benefits of innovation is hardly in dispute. Yet, it is equally important to recognise that innovation-driven growth models are not without their downsides. This, of course, is hardly a new observation in the literature. Concerns about the uneven patterns of regional development trace back to classic enquiries in economic geography (for recent contributions, see, e.g., Krugman, 1991; Storper & Walker, 1989; Cortinovis et al., 2024; Iammarino et al., 2019). More recently, scholars have noted that the costs and benefits of technological paradigm shifts – embodied, for instance, in the ongoing digital and green transitions – are strikingly uneven: these shifts open up new opportunities for certain regions to carve out specialisations in emerging industries, while leaving others at a disadvantage (e.g., Boschma & van der Knaap, 1997; Brezis & Krugman, 1997; Kemeny & Storper, 2020; Lee & Rodríguez-Pose, 2013; Rodríguez-Pose, 2012; Storper & Walker, 1989). This dynamic, coupled with the modularity and separability of production stages within global value chains dominated by large MNEs, seems to be intensifying inequality. Hence, scholars have noted that technological change may not only be widening the gap between the Global North and South but also deepening disparities within countries, regions, and even subnational areas such as cities and rural zones (Bair et al., 2021).

Despite these contributions, it appears that research in this area has been limited by two key shortcomings. First, it has largely accepted the notion that innovation and economic growth inherently foster greater well-being and prosperity, stronger institutions, and more peaceful societies, often neglecting the negative externalities that

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may arise from the commercialisation or production of innovations. Second, consequently, issues of social justice and the distributive challenges associated with an innovation-driven model of development have received comparatively less attention than the research focusing on its positive impacts.

Nelson and Winter (1982) described innovation as a 'process of change … continually tossing up new [negative] 'externalities' that must be dealt with in some manner or other' (p. 389). Spurred by mounting evidence of the detrimental effects that innovations embedded in socio-technical systems can impose on societies and the environment (Coad et al., 2021a), scholars of innovation have begun to turn their attention to a critical and overdue agenda: examining the darker side of innovation (Biggi & Giuliani, 2020; Coad et al., 2021b). Within this tradition scholars have generally questioned the assumption that market forces alone are sufficient to 'weed out the 'bad' innovations' (Coad et al., 2021b, p. 103; Gonzalez-Roma & Hernandez, 2018), while stressing an urgent need to realign technological progress with societal goals. In this context, research has rarely considered the geographical, and in particular the regional, dimensions of the drawbacks of innovation (Fitjar et al., 2019). Work in sustainability transitions has investigated the distribution of different transition processes across space and asked questions such as why transitions occur in one place and not in another, or about how different geographical contexts favour the transition from dirty to cleaner technologies (Hansen & Coenen, 2015). Likewise, scholars in economic geography have demonstrated a growing interest in the capacity of regions to produce green or eco-innovation (Hansmeier & Losacker, 2024; see also Hansmeier, 2021). These approaches aim to uncover patterns in the regional factors that drive technological change toward more sustainable or greener innovations. However, they pay far less attention to why certain regions become hubs for dirty technologies (with Biggi et al., 2024, providing a notable recent exception) or to the conditions under which innovations may result in significant societal and environmental harm.

Focusing on the negative effects of technological developments – at both global and local levels – is critical because it draws attention to a frequently overlooked issue: the irreversible impacts that certain technologies can have once they are deployed in the market (Rip & Kemp, 1998). These impacts, once set in motion, often shape society and the environment in ways that are difficult, if not impossible, to undo (Geels, 2004). This suggests that traditional cost–benefit analyses, which weigh the costs and benefits of innovation, may be inadequate for tackling major sustainability challenges (Giuliani, 2018). Some of the negative effects of innovation could have irreversible consequences that must be prevented or mitigated, regardless of the potential benefits. For this reason, they warrant careful scrutiny on their own merits.

This paper and those to follow in this collection discuss the dark side of innovation through economic geography lenses. We broadly consider the discrepancies between private and social benefits and costs involved in knowledge creation and diffusion across space. We discuss how innovation activities have geographically uneven outcomes, driving spatial inequality, and how they require material inputs located in certain places, meaning that their costs are also unevenly distributed across space. We structure the discussion around two main themes, reflecting the contributions to this collection on 'The Dark Side of Innovation and its Geography'. First, we examine the relationship between innovation and territorial inequality, before shifting focus to the geography of critical raw materials (CRMs) that are essential for today's most urgent innovation activities. In doing so, we integrate distinct strands of literature that, from various perspectives, have explored the hidden costs of innovation and their geographical impacts. Together – with an invitation for further research through a geographical lens – we aim to spark a debate and lay the groundwork for an ongoing conversation about the evolving relationship between innovation and regional economic development.

2. INNOVATION AND TERRITORIAL INEQUALITY

The discussion about the dark side of innovation is not new. Schumpeter (1942) argued that innovation has positive but also negative sides, and that the two are inextricably intertwined, a process which he dubbed creative destruction. A classic, well-documented example is the Luddite movement of cotton workers in Nottinghamshire that protested against the mechanisation of textiles in early 19th-century Britain (Sale, 1996). A current example is the impact of automation and artificial intelligence (AI), with its labour-displacing effects resulting in the disappearance of certain types of occupations (Acemoglu & Restrepo, 2019; Autor, 2015; Bessen et al., 2019). Some regions have high shares of jobs 'under threat' or jobs whose tasks will change (Felten et al., 2021; Muro et al., 2019). Consequently, the overall net effect of AI on jobs might be negative for some regions and positive for others (Zhang et al., 2024).

The potentially destructive forces of innovation on our entire economic system can be well illustrated by the example of financial innovations that contributed, among other factors, to the financial crisis of 2007–08 (Ülgen, 2014; Vives, 2010). New financial products in derivatives and securitisation had been introduced into the market, facilitated by a lax monetary policy and financial market deregulation preceding the crisis. These innovations led to bubbles in the housing and credit-supply markets that eventually burst. The crisis had major economic and social implications for many regions, leading to unprecedented levels of unemployment (Martin, 2011). Dörry (2022, in this collection) discusses the dark sides of financial innovations in major financial centres and the economic and social inequalities they generate.

The dark side of innovation is clearly visible when looking at intra-regional inequality. The most innovative cities in the United States are also often the most unequal ones (Florida, 2006). While this does not imply causation, the experience of Silicon Valley as the most innovative hub in the world is telling. Its unprecedented innovative success – mostly accruing to a few giant firms, the 'Big Tech' – has been accompanied by a sharp increase in intra-regional inequality, with a crowding out of the low-income population due to a lack of affordable housing (Gyourko et al., 2013). For European regions, studies have also found a positive relationship between innovation and wage inequality (e.g., Lee & Rodríguez-Pose, 2013). Research has established at least two mechanisms through which innovation can result in intra-regional inequality. First, the cost of living increases in innovative places, not least in the form of housing prices, as tech workers move in and displace low-income workers (Kemeny & Osman, 2018; Lee & Clarke, 2019). Second, there is a tendency of increasing labour market polarisation in large cities where high-wage workers benefit from technological progress and increase the demand for local services. This results in employment growth in low-wage jobs (Lee & Clarke, 2019; Moretti, 2010), while new technologies hollow out the middle segments of the labour market (Goos et al., 2014). The result is that large cities hosting highly complex activities, such as New York and San Francisco, show high and growing wage inequalities (Marco et al., 2022). The positive relationship between complexity and intra-urban inequality may be attributed to the coexistence of low- and high-complex activities in large cities, with relatively few job opportunities for middle-income people (Hartmann & Pinheiro, 2022).

Innovation also reveals its dark side when we examine its effects on interregional inequality. Through their network-based and platform monopoly, the Big Tech drain financial and human resources from other US regions, actively holding them back (Feldman et al., 2021; Ioramashvili et al., 2024). Many innovations, as measured by patents, are developed in core urban regions where high-quality research infrastructure, highly skilled people and knowledge diversity are heavily concentrated. This results in local accumulation of capabilities in a process which is cumulative, self-reinforcing and does not diffuse easily across space (Antonelli, 2000; Boschma, 2004), especially when it concerns complex technologies (Balland & Rigby, 2017). There is a super-linear relationship between patenting and urban size (Bettencourt et al., 2007a, 2007b; O'hUallichain, 1999; O'hUallichain & Leslie, 2005), especially in a-typical (Mewes, 2019) and complex technologies (Balland et al., 2020). This implies that innovation may reinforce, rather than weaken, centre–periphery structures. Wirkierman et al. (2024, in this collection) confirm this uneven geographical pattern when examining the role of trade and technological relations between regions in Europe. They observe a fractal structure of regional employment inequalities that is characterised by a centre–periphery structure between four trade blocks as well as inside each trade block in Europe.

This regional imbalance is not restricted to high-tech industries only but includes all kinds of activities. This is confirmed by another measure of innovation than patents: the ability of regions to diversify into new activities, such as industries or occupations. This topic has been taken up by Pinheiro et al. (2022, in this collection). From studies on regional diversification, it is well-known that regions tend to diversify into new activities that are related to existing ones in the region, following the principle of relatedness (Boschma, 2017; Hidalgo et al., 2018). Pinheiro et al. (2022, in this collection) show that this process of related diversification occurs in both high- and low-income regions. However, high-income regions tend to diversify into more complex activities, while low-income regions tend to move into less complex activities. High-income regions also have the highest potential to continue to enter into more complex technologies and industries in the years to come, given their strong local capabilities. This is likely to contribute to the widening of income disparities between regions, because complex activities on average pay higher wages and bring higher economic benefits to regions in terms of gross domestic product (GDP) growth (Rigby et al., 2022). This is a wicked problem for EU policy: the strategies to improve the innovativeness of Europe as a whole to compete globally might disproportionately benefit the more advanced regions, fostering even more interregional disparities.

Kemeny et al. (2022, in this collection) look at the distributional implications of the emergence of disruptive technological breakthroughs. Such breakthroughs are considered one of the key drivers of long-term economic growth (Esposito, 2023; Steijn et al., 2023) and may have the potential to destabilise centre–periphery structures and transform the geographical landscape of innovation (Boschma, 2021; Hall & Preston, 1988; Perez & Soete, 1988). Analysing patents over two Industrial Revolutions in the United States, they observe that disruptive technologies concentrate heavily in space. Their emergence is accompanied by increasing spatial income inequality, and technological leadership has shifted across Industrial Revolutions.

The concentration of innovation in large cities and core areas is often seen as a more or less natural trend, following automatically from the consolidation of the knowledge economy. This is reinforced by current approaches that consider regional development primarily as a function of innovation and endogenous growth, based largely on the experiences of advanced core regions (Marques & Morgan, 2021). Yet, as an emerging literature is pointing out, these trends are not equally present in all countries or for all technologies (Broekel et al., 2023; Fritsch & Wyrwich, 2021). Some peripheral regions are able to compensate for the lack of local buzz with more external networking (Fitjar & Rodríguez-Pose, 2011; Grillitsch & Nilsson, 2015), tranquillity (Gong & Xin, 2019), more multiplex interactions (Meili & Shearmur, 2019) and complementary interregional linkages (Balland & Boschma, 2021). From some perspectives, the periphery may even offer opportunities that core regions do not provide (Glückler et al., 2023). Less developed regions in the EU may have more opportunities to contribute to green technologies and innovation than advanced regions (Bachtrögler-Unger et al., 2023, p. 82). The idea that innovation mainly happens in cities may then to some extent be explained by the concentration of identification, marketing and promotion of innovations in urban areas (Shearmur, 2012), and of core regions' specialisation in certain highly attractive and profitable technologies. By extension, the effects of innovation on interregional inequality may not reflect higher levels of innovativeness in core regions as much as their ability to reap the returns of innovation, whether those innovations are developed in core or peripheral regions (Shearmur, 2016).

The role of policy in bringing about or preventing the dark side of innovation should therefore not be ignored. This of course includes laws and regulations, education and training, economic and monetary policy, etc., but also more narrowly defined innovation policy. As Lee (2023, in this collection) highlights, policymakers sometimes conceptualise innovation as being mainly about science, technology, engineering and mathematics (STEM), research and development (R&D), and high-tech industries. This leads them to search for competitiveness by establishing the Silicon Somewheres (Hospers, 2006) in which these sectors thrive. In such an approach, innovation policy should mainly foster industries which can attain globally leading positions within current technological paradigms: the result is that innovation policy tends to channel resources particularly towards core regions. This pattern is not exclusive to competitiveness-oriented innovation policy. It also affects mission-oriented innovation policies, which may also concentrate resources in communities that have the greatest potential to contribute towards the missions (Cappellano et al., 2023). Hence, rather than evening out the differences created by the market, government interventions may come to reinforce them. The idea is that these investments will generate trickle-down effects, either through market mechanisms or through redistributive policies, whether in the form of regional transfers or broader tax, labour or welfare policy. Yet, such positive spillover effects often fail to materialise and/or may be insufficient to compensate for core regions' higher levels of competitiveness and wealth.

One reason for the centralising tendencies of innovation policy is its inherent Matthew effects (Merton, 1968), whereby the initial leaders extend their advantage through self-reinforcing mechanisms. This is a well-known phenomenon in science and innovation, affecting citations and project funding, among other things (e.g., Bol et al., 2018). Matthew effects are reinforced by the increasing emphasis on excellence in the research policies of many countries (Langfeldt et al., 2015). Besides being relevant at the individual and organisational level, this also has implications for the geography of the distribution of research and innovation funding. Cities and regions that are endowed with leading research universities receiving more government base funding will be able to invest in facilities and in top researchers. Subsequently, this puts them in a better position to win grants through competitive funding schemes.

To escape this dark side of innovation, the perspective on what innovation policy is for must be broaden (Lee, 2024). We need to go from a narrow focus on the development of innovation to a broader perspective on how to ensure its diffusion, contrasting its adverse externalities, and paying attention also to the demand side of innovation (Coenen et al., 2015). Lee (2023, in this collection) examines inclusive innovation as a new policy approach which aims to widen participation and share the benefits of innovation. Yet, when implemented in practice, such policies are often ineffective, suffering from the same fixation on technology as traditional innovation policy. Conversely, there is also a need to examine more closely how some of today's innovations, for example, in the finance industry, channel wealth and power towards a small number of places. Dörry (2022, in this collection) shows how innovation in the asset management industry manipulates the global geography of profits from production.

This also involves a broader understanding of which industries can deliver innovation and of the different forms which innovation itself can take. Paying attention to low-tech industries and resource-based ones, and understanding how to use the assets that more peripheral regions can offer, are essential steps for developing innovation policies that can support the enhancement of opportunities in all regions.

3. AN EXAMPLE OF POLICIES FOR THE GREEN TRANSITION: THE RACE FOR CRITICAL RAW MATERIALS AND ITS REGIONAL FOOTPRINTS

The debate on critical raw materials (CRMs) – that is, rare metals such as cobalt, lithium, gallium and tantalum, or rare earth elements – illustrates the diverse forms in which innovation manifests, and the geographical unevenness of the associated costs and benefits. The topic has become increasingly hot worldwide, given the irreplaceable role of CRMs in providing a material infrastructure to emerging technologies and industries (e.g., Diemer et al., 2022, in this collection; Li et al., 2024). Green and digital technological transitions have put CRMs at the centre of the global resource competition: their availability, use and supply chain dynamics are shaping public and scholarly discussions on the economic futures of countries and regions.

The material infrastructure of technological change is by no means a new phenomenon. Innovations are first and foremost based on new combinations of 'materials and forces' (Schumpeter, 1934). Especially after the emergence of material science in the 20th century, technological development in a variety of fields has shown growing dependence on natural input materials, with paradigm shifts always closely related to change of materials, appearance of new ones, as well as new uses for those existing and the disappearance of those outdated and/or proven harmful (e.g., Dosi, 1982, 1988; Dosi & Nelson, 2010). Seminal work in economic growth theory has considered the interplay between technological change, availability of natural resources and economic growth (e.g., Acemoglu et al., 2012; Barbier, 1999; Bretschger, 2005; Solow, 1974; Stiglitz, 1974). In general, existing economics and innovation research provides important insights into the co-evolution of natural resource supply and technological change. However, most such studies rest on two strong assumptions, which have contributed to strengthening the general optimistic view of innovation. The first is that of substitutability between capital and resources or between different inputs, implying that the shortage of natural resources stimulates the generation of new technologies that make more intensive use of abundant resources as substitutes for scarce ones. Thus, technological innovation can solve, or at least improve, issues related to resource scarcity, enabling society to overcome resource supply constraints and achieve sustainable development. The second assumption is that the specific features of natural resource inputs such as materials are homogenous, and that such materials are generally available across space in an open world economy. Thus, growth models typically treat them as standard and a-specific production inputs freely accessible across countries and regions.

Clearly, this overall 'technology optimistic' perspective on natural resources is unable to consider the idea of criticality, which makes some materials indispensable for achieving certain technological functions, especially in frontier applications such as those in the current green transition (Grandell et al., 2016; Li & Iammarino, 2024). Hence, contemporary technologies and industries face often very limited options to circumvent CRM criticality, as for most of these materials 'no suitable substitutes can be found no matter what price is offered without performance and function being seriously compromised' (Graedel et al., 2015, p. 6299). On the one hand, technology optimistic views overlook the endogeneity of technological change to the natural environment: innovation itself may be adversely influenced by material and resource supply constraints, slowing down the green and renewable energy transition and causing environmental bottlenecks of a global nature. On the other hand, the optimistic perspective is non-specific and a-geographical, assuming that CRMs – highly heterogenous in their technological criticality – are evenly distributed or equally accessible across locations. In reality, private and social benefits and costs of the green transition have a highly situated nature (e.g., Barbieri et al., 2023, in this collection; De Marchi, 2024).

Studies on CRMs across disciplines have developed rapidly in recent years. The current literature, however, is mainly conducted at the global, national or sectoral level, focusing on metal mining, demand prediction, trade networks and material flow analysis, as well as supply risk assessment. Research on regional growth and development has instead almost entirely focused on the role of intangibles; physical materials, although constituting the basic building blocks of transition technologies as well as the primary constituents of renewable energy products, have been overlooked.

Why does all this matter for subnational regions in Europe and elsewhere? The EU is speeding up towards the target of climate neutrality by 2050, and CRMs provide a vital material basis for this shift. Recently, the issue of CRM supply risks – due to mineral scarcity, geographical concentration of deposits, political instability of producing regions, geopolitical risks and conflicts affecting global trade and investments, low material substitutability and recycling rates, and also potential pandemic and natural disasters – has made clear that the geography of such value chains matters (Diemer et al., 2022, in this collection), prompting policy actions for ensuring a more stable supply through domestic production. The EU Critical Raw Materials Act (European Commission, 2023), in line with the European Green Deal and as part of the wider EU Open Strategic Autonomy, is intended to make the EU more competitive and autonomous by promoting innovation along the entire value chain, upstream from CRM extraction and processing to renewable energy products, to new technologies on alternative materials and recycling, enhancing European supply according to environmentally friendly mining and production methods.[1] However, the EU remains highly vulnerable: the effort is to reach a target of at least 10% autonomy from imports, particularly from China, Russia and a number of developing economies where many such natural resources are abundant.

Private costs are the costs related to firms' decisions based on market prices: business companies are central actors upstream, in the mining, processing and organisation of CRM supply chains, and downstream, in the industrial and technological use of CRMs; profits are the benefits for such companies, mostly large MNEs at both ends of the chain. The socio-economic costs of the regions and their people are also at both ends of the value chain, which shows a multilayered unbalanced geography. On the supply side, CRM-producing regions and their communities – many in the Global South, but some also in Europe, mostly on its periphery – have to face serious environmental and social consequences of mineral exploitation and extraction. Whilst the EU regions involved may be able – with the help of place-specific innovation policies – to partly balance such costs by developing capabilities in high value functions, regions in poor countries such as, for example, the Democratic Republic of Congo (DRC) Copperbelt in Lualaba and Katanga provinces, see their precious geological resources failing to catalyse local economic development, MNE profits going abroad, benefits accruing to restricted national elites, and additional negative impacts in the form of conflicts and serious violations of human rights (e.g., Hilson et al., 2024). In the advanced nations, costs might be also compensated by the demand side: emerging industries requiring CRMs – for instance, core renewable energy sectors such as wind and solar energy products – are highly concentrated in a few EU regional innovation systems, where new technological trajectories are developing to ensure the green transition and achieve higher degrees of substitution and recycling of CRMs. This, however, tends to intensify the territorial concentration of wealth in the EU, as discussed above and by Barbieri et al. (2023, in this collection).

Yet, the wedge between benefits and costs, private and social, is complex to calculate precisely for its multilayer geography across the macro-areas of Global North and South. Environmental issues are global in nature but have highly local – regional – manifestations in relation to all dimensions that the green transition entails (Barbieri et al., 2023, in this collection). Benefits in terms of firms' growth and profits are not necessarily offsetting negative impacts such as, for example, environmental damages of extracting materials from the deep sea either in the Mediterranean or along the Atlantic southern cost of Namibia (e.g., Randazzo et al., 2024; Wiedicke et al., 2015). In Europe, the growing push from research and policy circles towards de-risking CRM supply chains through diversification of sources and increase of CRM domestic production cannot avoid looking more in depth at the subnational level. The Open Strategic Autonomy can be seen as a macro industrial policy with no regional focus but highly localised impacts at both ends – upstream and downstream – of the value chain.

Analysing such CRM-based value chains in their entirety across and beyond the EU territory is paramount to find new modes to build interregional cooperation and linkages among EU, often peripheral, mining regions, between them and EU regional centres of excellence for technological progress and advanced manufacturing, and crucially, between all EU regions involved and other regions in developing parts of the world where untapped reserves of many of these crucial natural resources are located. This is essential for leveraging opportunities for local and regional economic development during a costly transition, on the one hand, providing a sounder knowledge base to inform strategies for mitigating supply risks, and, on the other, ensuring truly fair and equitable exchange and partnership with less developed CRM-rich regions, starting with those in Sub-Saharan Africa, that have been systematically ignored in the distribution of the benefits of technological shifts (Hilson, 2016).

4. CONCLUSIONS

In this editorial, we have revamped an old discussion on the possible dark sides of technological innovation. While pioneering contributions in innovation studies pointed to negative effects of innovation on inequality and labour (Freeman et al., 1982; Schumpeter, 1942) and also hinted at the pollution-related externalities tossed up continuously by innovative processes (Nelson & Winter, 1982), this critical area of research has for some time remained in the shadow in favour of a more optimistic account of innovation impacts on societal well-being.

However, the emergence of new policy-relevant sustainability goals – including the need to reduce within- and cross-country inequalities, address political discontent, combat climate change and pollution – has crafted a new space for debating and exploring the role that innovation plays in meeting these goals. While, again, a significant body of research is now looking at innovation as a technological fix for the many sustainability challenges – consistent with the rising body of evidence on green, inclusive or otherwise defined social innovations – we suggest here that scholars should be equally interested in critically assessing the consequences of regular innovations for society and the natural environment, and how they affect regions of the world very differently. Investigating the dark sides of innovation means studying its harmful consequences for society and the environment. In regional studies, the spatial dimensions of these consequences are of particular interest.

This collection includes contributions that add a geographical perspective to the discussion on the dark side of innovation by exploring the regional distribution of the benefits of innovation and of its costs. On the one hand, we highlight the effects of the polarisation of regional innovation in core regions on increasing spatial inequalities. On the other, we explore the concentration of the costs of innovation in some peripheral regions of the world, North and South. Here, as an example, we stress the need to reframe sustainability transitions policies in light of the manifest dependency of green technologies on CRM-providing regions, where extraction of critical natural resources is known to occur below acceptable Western human rights and environmental standards. While these two areas of enquiry are significant and complex enough to call for more research in the future, we would also recommend other potential areas of interest that this collection has not been able to cover but that certainly deserve closer scrutiny.

One possible area of interest is the geography of substitution between clean and dark (or dirty) innovations. As evidence suggests that dirty innovations are path dependent (Aghion et al., 2016; Biggi et al., 2024), questions arise about how long it will take for cleaner innovations to supplant dirty ones and whether there is a geography of innovation that differently characterises dirty and green innovations. These questions are even more relevant considering the EU Green Deal oath to 'do no harm' and its zero-pollution ambitions, as one important side of reducing pollution is through the phasing out of dirty innovations used in the market. To date, there is very limited knowledge about the geography of dirty inventions and whether and how the regions that are leaders in these technologies are also becoming leaders in their cleaner substitutes. Nor do we know, in the current multi-polar world, whether regions specialising in dirty technologies – both in invention and production – are different from those specialising in cleaner alternatives – as sometimes the knowledge base is radically different.

A related area of enquiry is around the link between pollution and innovation. Research in environmental studies has already started to assess whether air pollution decreases regional innovation through the crowding-out of skilled human resources moving to safer regions (Wang et al., 2024). Other studies look at the extent to which greener innovations emerge out of the most polluting organisational or spatial contexts (Li et al., 2022; Wang et al., 2022). As pollution is certainly one of the key sustainability challenges of our times and given the geographical concentration of pollution in toxic hotspots – locations where toxic emissions from production plants or other primary activities may expose local populations to elevated health risks – research providing evidence of its link to innovation is worth pursuing. Toxic hotspots are, in fact, a manifestation of the dark side of past industrial innovations (Shapira & Zingales, 2017) and their legacy and impacts on local communities is highly relevant to development policies.

Overall, we call for new theoretical and empirical research in innovation studies, taking into account both positive and negative socio-economic effects of innovation across space, its bright and dark sides in different places, and developing new conceptual and methodological tools to study, compare and assess multidimensional and contrasting effects of innovations in a broader interdisciplinary framework. This new departure will entail an in-depth discussion of how to capture the balance of the effects of innovation at the regional level, how to measure them, and how to assess their benefits and costs according to different social welfare functions and institutional settings.

These issues do have important implications for R&D and innovation, and more generally economic development policy. Since innovations and technologies have complex and multidimensional effects – positive and negative, economic and non-economic, at different levels of geography – how can policymakers assess and define whether a given innovation process should be given public support, or instead regulated and limited? The multidimensional and complex nature of innovation processes and their spatially uneven footprints present policymakers with a variety of trade-offs and complex choice sets, which call for a continuous development of new conceptual and methodological tools.

To be sure, we do not mean to build a 'silo-type' conversation where social, environmental and human rights issues are seen as hyper-specialised side topics of no interest to innovation studies, economics, international business or economic geography and regional studies. Rather, we want to promote a discussion where considerations about regional economic development (and growth) are balanced with innovation-related side effects, bright and dark, across the regions of the Global North and South.

NOTE

1. See https://www.europarl.europa.eu/news/en/press-room/20231208IPR15763/critical-raw-materials-plans-to-secure-the-eu-s-supply/.

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