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THE IMPACT OF DIGITALISATION ON THE ENVIRONMENT: A REGIONAL PERSPECTIVE

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Abstract

Digitalisation and environmental transition are transforming regional economies in connected yet uneven ways. While digital progress can improve efficiency and organisation, it can also create new habits, increase material demand, and widen existing disparities. This thesis explores how these processes interact, examining when and where digitalisation supports, or instead slows down, progress towards decarbonisation. The research begins with a review of the literature, identifying the main conceptual and empirical gaps that have limited the understanding of the digital-environment link. These insights form the basis for the rest of the work. Grounded in the idea that transitions are never spatially neutral, the thesis adopts a regional approach that looks across different scales. It first focuses on Italy, showing that the spread of digitalisation is linked to improvements in environmental quality and that these benefits extend beyond administrative borders, revealing spatial spillovers. It then moves to the European level, highlighting how the relationship between digitalisation and emissions varies across regions and stages of the decarbonisation process. Bringing together conceptual reflection and empirical evidence, the thesis shows that the connection between digitalisation and the environment is deeply shaped by place. It argues that the success of the twin transition depends on recognising geography as a driver of change – one that determines where, how, and for whom digital progress becomes a path towards environmental resilience.

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Chapter 1

Introduction

1.1 Environmental and digital transformation: conceptual foundations

1.1.1 Framing the environmental challenge

Climate change represents one of the most pressing challenges of the 21st century, driven by the persistent accumulation of greenhouse gases (GHG) in the atmosphere. The Intergovernmental Panel on Climate Change (IPCC 2023) has shown that global average temperatures have increased by roughly 1.1°C over pre-industrial levels, predominantly due to human-induced emissions. The recent AR6 Synthesis Report indicates that existing global policies are leading the world towards a warming trajectory significantly exceeding the 1.5 °C threshold established by the Paris Agreement, with global GHG emissions in 2019 being 59 $GtCO_2$ equivalent – 54% greater than in 1990. Without profound, rapid, and consistent reductions across all sectors, achieving a temperature increase limit of 1.5 °C or even 2 °C will remain out of reach.

The European Union (EU) serves as both a contributor to and a leader in combating climate change. The EU constitutes approximately 7% of global GHG emissions,

however it has significantly decoupled emissions from economic development. The European Commission's Climate Action Progress Report (European Commission 2024a) indicates that by 2022, EU GHG (excluding land use, land-use change, and forestry) had decreased by 37% relative to 1990 levels. If sustained and intensified, this reduction trajectory places the EU near its legally mandated aim of a 55% net emissions reduction by 2030, as defined in the European Climate Law (European Parliament and Council of the European Union 2021).

The European Environment Agency (EEA) warns that further efforts are needed to achieve the 2030 goal, especially in sectors where emissions have been more resistant to reduction, including transport, agriculture, and specific industrial segments. In 2022, transport constituted about 23% of EU GHG, with road transport contributing over 70% of this proportion (EEA 2024). Although emissions from the power sector have markedly diminished owing to the implementation of renewable energy sources, advancements in the transportation and agricultural sectors have been more gradual, partially because to structural and behavioural influences.

The State of the Energy Union report (European Commission 2024b) underscores that attaining carbon neutrality by 2050 necessitates a comprehensive restructuring of energy infrastructures, industrial processes, and consumption patterns. The energy sector continues to be the predominant source of emissions; but the growing electrification of transport and industry redirects the task to guaranteeing that power generation is both adequate and entirely decarbonised. Simultaneously, structural enhancements in energy efficiency are essential to temper demand growth, especially with the expansion of digital infrastructure and electrified transportation.

The urgency is exacerbated by the environmental and socio-economic effects currently being experienced. Climate change has exacerbated the frequency and intensity of extreme weather events throughout Europe, encompassing heatwaves, droughts, floods, and wildfires (EEA 2024). These occurrences incur substantial economic expenses, disrupt supply chains, and intensify disparities both between and within areas. Coastal regions face increasing challenges from sea-level rise, and agricultural areas grapple with crop instability and water scarcity.

The EU has integrated climate targets into its overarching economic policy, particularly via the European Green Deal (European Commission 2019b), which positions climate neutrality as an environmental imperative and an economic prospect. This vision emphasises that mitigation cannot be accomplished by mere incremental enhancements; it necessitates a fundamental reform of production and consumption systems. This transformation involves changes in the energy mix and industrial processes, as well as the implementation of innovative technologies, novel business models, and behavioural changes across all societal levels.

In this setting, the digitalisation has gained increasing importance. Digital technologies provide robust instruments for improving efficiency, maximising resource utilisation, and facilitating low-carbon innovations across several sectors.

1.1.2 Unpacking digitalisation

In recent decades, the diffusion of digital technology has transformed economic frameworks, the organisation of public services, and the interactions between households and firms (European Commission 2020b). This transformation is commonly framed as part of the Fourth Industrial Revolution, wherein enhancements in connectivity, computational capacity, and data accessibility combine to redefine industrial systems, governance, and social dynamics (Schwab 2017; UNCTAD 2019).

These changes are often grouped under the umbrella of *digitalisation*, although the term hides substantial differences that clarify the scope and depth of digital transformation. According to Vrana and Singh (2025), *digitisation* denotes the transformation from analogue information into a digital format suitable for electronic processing, storage, and transmission – a process linked to the initial stages of the digital revolution and centred on the technical encoding of data. *Digitalisation* leverages this power by employing digital technology to alter or re-engineer processes, products, and services. This phase is characterised by the restructuring of organisational frameworks, service provision, and methods of engagement. *Digital transformation* includes the structural and cultural changes that arise when

digitalisation is thoroughly integrated into economic and social frameworks. It signifies a comprehensive transition to novel operational frameworks, governance systems, and societal norms, facilitated by the widespread incorporation of digital technologies.

Within the European framework, digitalisation is considered as a catalyst for value generation, competitiveness, and social inclusion (European Commission 2020b). Its impact extends across various sectors. The incorporation of industrial Internet of Things (IoT), Artificial Intelligence (AI), and advanced robots in production has facilitated predictive maintenance, mass customisation, and enhanced resource efficiency. In public administration, interoperable e-government platforms have streamlined processes and enhanced accessibility for citizens and firms. In agriculture, precision farming technologies using satellite data and sensors have enhanced input efficiency and increased yields.

The revolutionary potential of digitalisation is coupled with a markedly uneven rate of advancement across sectors, geographies, and demographic groups. The European Commission's assessment via the Digital Economy and Society Index (DESI) indicates that Member States are progressing at varying rates, with some positioned as global leaders in digital skills, infrastructure development, and the integration of advanced technologies in business, while others continue to experience significant deficiencies in one or more of these areas (European Commission 2022). These discrepancies are influenced by various factors, such as the economic sector composition, the prevalence of innovation-driven enterprises, the availability of trained workers, and the existence of supportive digital ecosystems (OECD 2022). Regional disparities are pronounced: innovation centres and urban locales frequently exhibit elevated adoption rates of sophisticated digital technologies and enhanced integration into global value chains, while structurally disadvantaged or isolated regions encounter greater challenges in mobilising the resources, competencies, and networks necessary for digital transformation (Reveiu et al. 2023; Gomes and Dias 2025).

Understanding digitalisation as a multifaceted process – encompassing technological, organisational, economic, and social dimensions – provides the basis for

evaluating its interplay with other structural developments. Its capacity to produce efficiency improvements and systemic optimisation closely correlates with the environmental transformation, yet its material demands and energy consumption impose more sustainability challenges. The dual nature places digitalisation at the core of the ongoing discourse around the twin transition, which will be examined in the subsequent section.

1.1.3 Twin transition

The twin transition concept refers to the strategic recognition – particularly within the EU – that digital and green transformations are interdependent and should be advanced in parallel (European Commission 2021b; Muench et al. 2022; Bassot 2024). It emerged in the policy debates surrounding the European Green Deal and the 2030 Digital Compass (European Commission 2019b; European Commission 2021b) and has since been integrated into many EU frameworks and national strategies. The core assumption is that digital technologies can accelerate the decarbonisation of economic systems, while the green transition sets the environmental parameters and sustainability goals that digital systems must respect.

The 2030 Digital Compass defines four pillars for Europe's digital decade – digital skills, secure and sustainable infrastructures, business digital transformation, and the digitalisation of public services – and explicitly links their achievement to the objectives of the European Green Deal (European Commission 2021b). It also sets measurable targets such as universal gigabit connectivity, 5G coverage in all populated areas, 80% of adults with basic digital skills, and 75% of enterprises using cloud computing, big data or artificial intelligence by 2030. Sustainability is embedded through objectives for energy-efficient and climate-neutral infrastructures, including a commitment to climate-neutral data centres by 2030.

The European Green Deal (European Commission 2019b) frames climate neutrality by 2050 as a central goal and introduces cross-sectoral initiatives – such as the Renovation Wave, the Sustainable and Smart Mobility Strategy, and the Farm to

Fork Strategy – many of which rely on digital solutions for monitoring, optimisation, and performance assessment. The Joint Research Centre's Digital for Green report (Muench et al. 2022) further illustrates how advanced data analytics, the IoT, and AI can enhance environmental monitoring, optimise resource use, and improve systemic efficiency.

The interdependence between the two transitions operates in multiple directions. Digital technologies can enhance sustainability by improving efficiency, optimising resource allocation, and enabling predictive capabilities. Examples include smart grids that balance electricity supply and demand in real time, intelligent transport systems that reduce congestion and fuel consumption, precision agriculture that optimises water and fertiliser use, and advanced modelling tools that improve climate forecasting. These applications can deliver significant reductions in GHG emissions and other environmental pressures, especially in energy-intensive sectors such as manufacturing, transport, and construction.

At the same time, the deployment of digital technologies creates environmental challenges of its own. The rebound effect – where efficiency gains reduce costs and trigger additional consumption – can offset or even reverse expected emission reductions (Muench et al. 2022). The growth of data-intensive services, connected devices, and high-capacity networks increases energy demand and, in the absence of clean power, associated emissions. Data centres already account for a significant share of electricity use in Europe, while the production of digital equipment depends on critical raw materials, raising concerns over resource scarcity and supply chain sustainability. The twin transition therefore requires active management of the digital sector's footprint to ensure that technological advances contribute positively to climate and sustainability objectives (Peng et al. 2023).

The EU has embedded the twin transition across several key policy instruments:

- European Green Deal (2019), the overarching strategy that commits the EU to climate neutrality by 2050, with an interim target of at least 55% emissions reduction by 2030 (European Commission 2019b).
- The Circular Economy Action Plan (2020) argues for digital solutions per-

taining to product passport systems, waste tracking, and resource efficiency. Blockchain and IoT technologies are anticipated to monitor material movements and improve transparency in value chains, hence promoting environmental sustainability and competitiveness (European Commission 2020a).

- 2030 Digital Compass and Digital Decade Policy Programme (2021–2022) translates the EU's digital ambitions into measurable targets, ensuring alignment with sustainability goals (European Commission 2021b).

- The Fit for 55 Package (2021) is a comprehensive legislative initiative that implements the Green Deal's 2030 objectives. It amends the EU Emissions Trading System, enhances CO_2 emission requirements for automobiles, and implements the Carbon Border Adjustment Mechanism. Digitalisation facilitates these reforms by enhancing data collecting, monitoring, and compliance verification, while also enabling intelligent charging and demand-response mechanisms in the energy sector (European Commission 2021c).

- EU Industrial Strategy (2020, updated 2021) seeks to establish a competitive, sustainable, and digital industrial foundation. It promotes the adoption of sophisticated digital tools in energy-intensive sectors to enhance efficiency and mitigate emissions, while also facilitating the advancement of clean technology, such as digitalised manufacturing processes for renewable energy components (European Commission 2021d).

The EU establishes the overarching strategic framework for the twin transition, but its successful execution relies on state policies that tailor European priorities to local conditions. In the Italian context, three principal initiatives correspond with EU objectives:

- National Recovery and Resilience Plan (NRRP, 2021). It comprises six missions, with the first two central to the twin transition. Mission 1 invests resources towards digitalisation, innovation, and competitiveness, emphasising digital public services, broadband infrastructure, and the digital transformation of enterprises. Mission 2 focusses on the green revolution and ecological transition by financing renewable energy projects, building

renovations, sustainable transportation, and circular economy initiatives (Governo Italiano 2021).

- National Strategy for Ultra-Broadband – Italy at 1 Giga (2021). This initiative is integral to Italy's comprehensive digital infrastructure policy, guaranteeing nationwide high-speed connectivity and facilitating the implementation of digital services that promote environmental goals, including remote energy management, precision agriculture, and telecommuting in rural regions to mitigate commuting emissions (Ministero delle Imprese e del Made in Italy 2021).

- National Strategy for Sustainable Development (SNSvS, 2022). It establishes the comprehensive framework for Italy's sustainable development policies, in accordance with the UN 2030 Agenda. It emphasises the significance of digital technologies in facilitating environmental monitoring, sustainable urban mobility, and efficient resource utilisation, including them into comprehensive environmental governance frameworks (Ministero dell'Ambiente e della Sicurezza Energetica 2022).

These policy frameworks exhibit a common rationale: the green and digital agendas are regarded not as distinct pathways, but as interconnected elements of a comprehensive transformation plan. This entails synchronising investment strategies, regulatory structures, and innovation incentives to ensure that advancements in one area bolster progress in another. The digitalisation of energy systems – via smart meters, predictive analytics, integrated grid management – facilitates renewable integration and demand-side flexibility, while the decarbonisation of the Information and Communication Technologies (ICT) sector through renewable-powered data centres and circular design principles mitigates its environmental impact. Nonetheless, the incorporation of the twin transition into policies does not ensure flawless execution. Divergences in economic frameworks, technological preparedness, and institutional capabilities generate disparities in the speed and efficacy with which regions and sectors can implement solutions consistent with the twin transition. Rectifying these inequities necessitates both financial investment and focused assistance for skills enhancement, innovation dissemination, and

governance capacity at the local level.

1.2 A territorial approach to digital-environmental dynamics

The twin transition of digital and green transformations is frequently addressed at the European or national level, when policies and objectives are formulated. However, its actual execution and effects are inherently territorial. Regions represent areas where infrastructures are built, enterprises use technology, and communities encounter both the advantages and disadvantages of transformation. The disparities in industrial frameworks, institutional capabilities, demographic makeup, and environmental circumstances result in the uneven distribution of pathways and results associated with the twin transition across different regions.

This territorial aspect also indicates that neither digitalisation nor environmental processes conform to administrative boundaries. Data networks, innovation ecosystems, and labour markets frequently transcend national boundaries, yet environmental issues like air pollution, water management, and biodiversity loss manifest at functional ecological scales.

1.2.1 Why the regional scale matters

The regional scale serves as both a functional observation level and an essential analytical framework for comprehending the diversity of outcomes and the reciprocal interaction among territories.

From a structural standpoint, European regions vary in industrial mix, technological capabilities, human capital resources, and infrastructure quality. These disparities influence both the capacity of digital technologies to advance environmental goals and the ecological ramifications of their implementation. Regions specialising in knowledge-intensive services with strong ICT sectors can more easily incorporate advanced digital tools into decarbonisation programmes. In contrast,

areas characterised by energy-intensive manufacturing or lacking robust innovation ecosystems may implement similar technologies without realising equivalent environmental benefits and may even witness short-term rises in emissions due to rebound effects and dependence on carbon-intensive energy sources (OECD 2019; Capello and Lenzi 2013).

Nonetheless, variability in outcomes is not solely determined by local variables. Economic, technical, and environmental processes demonstrate geographical interconnection. Regions are integrated within networks of commerce, knowledge transfer, and environmental externalities: the implementation of digital solutions in one area can disseminate to adjacent regions via supply chains, workforce mobility, and policy imitation, while environmental consequences such as air pollution or fluctuations in electricity demand frequently transcend administrative borders. Spatial dependence indicates that a region's trajectory cannot be comprehensively described in isolation; it is partially influenced by changes in neighbouring or functionally related regions (Anselin 1988; LeSage and Pace 2009).

Acknowledging the combined significance of heterogeneity and dependence is crucial for the twin transition. Policies that fail to consider these geographical factors may exacerbate existing inequalities. Empirical evidence from European innovation systems indicates that "twin innovators" – regions proficient in both green and digital innovation – tend to cluster spatially, whereas non-innovators frequently remain confined to low-performance equilibria. Transitions between states are more likely in places already aligned with ICT compared to those with an exclusively green specialisation, highlighting the significance of initial conditions and closeness to dynamic peers (Fazio et al. 2025). These clustering patterns suggest that spatially concentrated capabilities and interregional connections might enhance benefits while also consolidating disadvantages.

The regional scale serves as the operational domain for a significant portion of the EU's place-based policy framework. The Cohesion Policy and Smart Specialisation Strategies (S3) specifically focus on NUTS-2 regions, matching investment objectives with regional strengths and vulnerabilities (Foray et al. 2012; European Commission 2023). This approach embodies the idea that growth

driven by innovation – and consequently, the twin transition – is more efficacious when interventions are customised to the specific industrial composition, skill set, and governance frameworks of a region (Barca et al. 2012; Rodríguez-Pose 2018). This indicates that a region's capacity to utilise the twin transition relies on the coordination of digital infrastructure implementation, clean energy accessibility, and institutional capability to manage multi-sectoral policies. Institutional capacity itself is highly uneven across regions. Strong regional administration may combine digital and environmental goals into cohesive programmes, oversee intricate funding sources, and promote stakeholder collaboration among public, corporate, and research sectors. In contrast, inadequate capability may result in fragmented initiatives and inefficient resource utilisation, even in the presence of national or EU-level support. The Territorial Just Transition Plans (TJTPs) of the Just Transition Mechanism acknowledge the necessity for localised diagnostics and strategies, incorporating measures for skills enhancement, industrial diversification, and infrastructure investment in regions significantly impacted by decarbonisation (European Commission 2020c).

The significance of the regional scale is further underscored by the characteristics of both digital and environmental indicators. A variety of relevant metrics – such as broadband penetration, advanced technology adoption rates, and GHG emissions per capita – are observed at the regional level, facilitating the recognition of spatial trends. The spatial analysis of this data determines if regions are converging or diverging in their twin transition progress and whether advancements in one location correspond with alterations in its neighbouring areas.

Moreover, environmental and digital revolutions frequently necessitate physical – data centres, renewable energy generation facilities, charging networks – that is anchored in particular locations yet supports broader functional regions. Decisions regarding the placement of these assets influence regional disparities: concentration in already affluent and well-connected areas may intensify divides, whereas strategic positioning in underdeveloped regions can promote both economic and environmental enhancement (European Commission 2023). A territorial strategy facilitates the intentional use of infrastructure investment as a mechanism for spatial rebalancing.

The economic geography of innovation further supports a regional emphasis. The spread of digital-green technology is dependent upon proximity to centres of expertise, suppliers, and early adopters. Agglomeration economies promote experimentation, learning, and adaptation; nevertheless, without specific interventions, peripheral regions may be marginalised from growing value chains (OECD 2020). This dynamic is reflected in environmental challenges: transboundary river basins, international air sheds, and shared ecosystems necessitate coordinated management, typically occurring at the level of neighbouring regions rather than solely at national or EU levels (European Commission 2019a).

1.2.2 Spatial dependence and spillover dynamics

Spatial dependence refers to the systematic correlation of values seen across various spatial units, influenced by geographical proximity or functional relationships (Anselin 1988). This notion illustrates that regions are integrated inside networks – economic, infrastructural, environmental – where actions or conditions in one area can affect results in another. In empirical analysis, spatial dependence is frequently described using spatial lags, applicable to the dependent variable (spatial lag models), explanatory variables (spatial Durbin models), or the error term (spatial error models) (LeSage and Pace 2009; Elhorst 2014). In the context of the twin transition, spatial dependence indicates that advancements in digitalisation or environmental performance in a location cannot be comprehensively understood without accounting for improvements in adjacent areas.

The concept of spillover effects refers to the spread of impacts – whether positive or negative – beyond the geographical boundaries where they originate. In innovation studies, spillovers refer to the phenomenon whereby knowledge or technological advancements generated in one area augment capabilities in another without corresponding local investment (Audretsch and Feldman 2004; Autant-Bernard et al. 2007). In environmental economics, spillovers typically represent transboundary phenomena in pollution distribution, resource movement, and ecosystem interactions (EEA 2019). For the twin transition, these effects can be categorised into multiple interconnected classifications:

- Technological spillovers. They occur when the advancement or implementation of novel technology in one area promotes innovation in another. In the digital-green sector, this may happen through the dissemination of smart grid management software, AI-driven energy forecasting tools, or precision agriculture platforms from technologically advanced areas to others via supply chains, industry associations, or collaborative initiatives (Audretsch and Feldman 2004; Autant-Bernard et al. 2007). The magnitude of these spillovers is depending on geographical proximity, sectoral relatedness, and the absorptive ability of the receiving region (Crescenzi and Rodríguez-Pose 2011).

- Environmental spillovers. Environmental impacts frequently transcend administrative boundaries. Reductions in emissions in one area can enhance air quality and decrease greenhouse gas concentrations in adjacent regions. Whereas adverse effects, such as "pollution leakage", could arise if stringent environmental regulations in one area prompt the migration of polluting activities to regions with less stringent oversight (Copeland and Taylor 2004; EEA 2019).

- Infrastructure spillovers. Substantial investments in infrastructure – such as renewable energy generation facilities, energy storage systems, internet networks, and electric car charging corridors – frequently confer advantages to several regions beyond the host site (OECD 2019). Renewable energy implementation in a certain location can facilitate the decarbonisation of interconnected power markets, hence diminishing marginal emissions in other areas (Stiewe et al. 2025). In contrast, uncoordinated investments may result in bottlenecks and underutilised capacity.

- Institutional and policy spillovers. Governance frameworks, policy instruments, and regulatory innovations established in one region might be emulated in others. The effective integration of digitalisation and environmental goals – exemplified by smart city initiatives that merge real-time mobility data with low-emission zones – can be replicated via EU-funded collaborative frameworks such as INTERREG (European Union 2023). Nonetheless, policy

spillovers may induce competitive pressures for identical investment or talent pools, resulting in disproportionate net gains.

Hence, the effects of the twin transition are dual. Technological and environmental trajectories are interlinked spatially; advancements in one area, like renewable energy implementation, might catalyse enhancements in others via shared marketplaces and supply chains (Stiewe et al. 2025). Secondly, unregulated adverse spillovers – such as emission displacement, digital disparities, or congestion in shared infrastructures – can offset local benefits and compromise overarching sustainability objectives (EEA 2019).

Spatial econometrics provides methodologies to discern and quantify these relationships. Models that include spatial lags of dependent variables, explanatory variables, or error terms facilitate the estimation of both direct effects (within-region) and indirect effects (between-region) (LeSage and Pace 2009). When applied to the twin transition, these models can evaluate whether enhancements in broadband penetration or renewable capacity in one area systematically affect environmental or digital indicators in adjacent regions.

1.2.3 Spatial heterogeneity

In spatial econometrics, spatial heterogeneity refers to systematic variations in relationships or processes across space, meaning that parameters differ by location rather than being constant for the entire study area. By contrast, spatial dependence concerns correlations between neighbouring units, whereas heterogeneity reflects structural differences that lead identical changes in a predictor variable – such as the implementation of digital infrastructure or the expansion of renewable energy capacity – to produce different outcomes depending on local characteristics (Anselin 1988; LeSage and Pace 2009; Elhorst 2014).

The disparities in EU regions influence both the capacity of digitalisation to advance environmental goals and the ecological consequences of digital adoption. A rise in broadband penetration may yield substantial efficiency improvements in a knowledge-driven urban economy, yet exert a more limited environmental effect

in a manufacturing-centric area dependent on fossil fuels (Capello and Lenzi 2013).

The factors shaping regional heterogeneity in twin transition dynamics can be grouped into several interrelated dimensions:

- Economic and industrial framework. Regions specialising in high-tech services or advanced manufacturing typically adopt digital technologies more swiftly and leverage them for sustainable outcomes. Conversely, regions reliant on energy-intensive industries may experience slower improvements or even temporary increases in emissions when adopting digital processes (Frenken et al. 2007; Capello and Lenzi 2013).

- Innovation capacity and human capital. The presence of research institutions, innovative enterprises, and skilled workers enhances a region's ability to create and apply new technologies, while limited human capital constrains the translation of digital investments into environmental benefits (Crescenzi and Rodríguez-Pose 2011).

- Infrastructure endowment. Adequate digital (e.g., broadband, 5G) and energy (e.g., smart grids, renewable generation) infrastructures are prerequisites for realising the benefits of digital-green integration. Peripheral regions often lag behind in both, reducing potential returns (European Commission 2023).

- Institutional quality and governance capacity. Effective governance enables integrated strategies, stakeholder engagement, and efficient use of EU and national funds, whereas weak institutions risk fragmented or poorly targeted actions (Rodríguez-Pose 2018).

- Path dependency and technological lock-ins. Historical specialisations affect current adaptive capacity. Regions embedded in carbon-intensive production systems or outdated ICT infrastructures face higher transition costs and risk "lock-in" to suboptimal trajectories (David 1985; Martin and Sunley 2006).

- Geographic and environmental context. Climate, resource endowments, and connectivity influence the feasibility and impact of twin transition strategies. For instance, solar photovoltaic deployment potential varies substantially

between Mediterranean and Nordic regions, shaping the cost-effectiveness of specific digital-green solutions (European Environment Agency 2021).

Empirical evidence from the EU suggests that these differences lead to non-uniform policy impacts. Studies on regional innovation show that interventions such as Research & Development subsidies or infrastructure investments often generate stronger results in regions with complementary assets, while less-developed areas require additional support to achieve similar outcomes (Crescenzi and Rodríguez-Pose 2011; McCann 2020). In the twin transition context, this means that identical policy measures may yield divergent environmental results depending on regional preparedness.

The European Union's policy framework increasingly recognises spatial heterogeneity. The principle of smart specialisation under Cohesion Policy calls for aligning innovation priorities with regional strengths and potentials (Foray 2015). The TJTPs tailored to the socio-economic profiles of affected regions, acknowledging that decarbonisation pathways differ across space (European Commission 2021a). The 8th Cohesion Report further stresses that achieving the green and digital targets of the 2030 Digital Compass and European Green Deal demands differentiated strategies that reflect regional diversity (European Commission 2023).

From a methodological perspective, ignoring spatial heterogeneity can lead to biased or misleading estimates. Global regression models impose a single parameter value for all observations, thereby masking differences and potentially overstating impacts in some regions while understating them in others (Elhorst 2014). To overcome this, approaches such as Geographically Weighted Regression, spatially varying coefficient models, and spatial quantile regression allow relationships to vary across locations and along the conditional distribution of outcomes, providing richer insights than global models (Brunsdon et al. 1996; Fotheringham et al. 2002; Gelfand et al. 2003; Cartone et al. 2021).

For the twin transition, these methods can reveal whether digitalisation produces stronger environmental benefits in certain regions – such as urban, innovation-driven areas – or whether negative effects (such as rebound phenomena) are more pronounced elsewhere. Such insights are essential for designing place-sensitive

policies that match measures to local conditions, rather than assuming a one-size-fits-all approach.

1.3 Addressing the gaps in the literature

Despite the rapid expansion of studies on the relationship between digitalisation and the environment in recent years, critical gaps remain, hindering a comprehensive understanding of these interactions. Much of the existing research has developed along distinct strands: assessments of the environmental footprint of ICT, analyses of digital tools as enablers of decarbonisation, and sector-specific studies of particular technologies. However, these strands often lack a cohesive framework that integrates different perspectives. As a result, the literature frequently provides fragmented or incomplete insights, neglecting broader conceptual, methodological, and spatial dimensions. Recognising these limitations is essential, as they shape the research strategy of this thesis and inform the specific contributions developed in the following chapters.

1.3.1 Limitations in current literature reviews

The body of literature connecting digitalisation and environmental sustainability has grown significantly, alongside the number of reviews in this field; yet persistent limitations remain. The first limitation concerns the binary characterisation of effects. Many reviews reduce the debate to whether digital technologies are "advantageous" (through efficiency gains and optimisation) or "harmful" (owing to ICT-related energy use, material demands, and e-waste generation), overlooking cases where impacts are mixed, non-linear, or negligible. For example, early stages of digital diffusion may coincide with rising emissions before efficiency gains materialise (Charfeddine and Umlai 2023; Mouthaan et al. 2023). This evidence suggests the inclusion of a third category – beyond simply "positive" or "negative" – to capture complex or insignificant environmental implications of digital technologies.

A second limitation relates to conceptual and measurement consistency. *Digitalisation* is operationalised through a wide range of indicators, including broadband coverage, network diffusion, usage intensity, and the adoption of specific technologies such as cloud computing or artificial intelligence. Yet these dimensions are rarely integrated into a coherent framework that connects them to environmental outcomes. Systematic reviews and bibliometric analyses reveal a fragmented body of research organised into thematic silos (by sector, technology, or level of analysis), which complicates the accumulation of evidence and the comparability of results across contexts and time (Guandalini 2022).

A third limitation is the lack of comparative and up-to-date perspectives. Many contributions investigate specific components, but these are seldom embedded in comparative frameworks that could highlight broader patterns across sectors or regions. Even the most comprehensive reviews which cover the period 2000–2022, typically conclude before 2022, underlining the need for regular updates that reflect the latest dynamics of digital transformation (Guandalini 2022; Charfeddine and Umlai 2023).

Taken together, these gaps indicate that the literature has not yet developed a sufficiently cohesive and systematic framework to capture the complex interplay between digitalisation and environmental sustainability. This underscores the need for further research that moves beyond binary framings, fragmented indicators, and narrow sectoral studies.

1.3.2 Gaps in accounting for spatial dependence

When turning from literature reviews to applied empirical research, a number of additional gaps become evident. A first gap concerns the absence of systematic evidence regarding environmental outcomes. Although digitalisation is frequently linked to both beneficial and detrimental outcomes, scientific evidence remains disjointed and occasionally inconsistent. Numerous studies investigate particular elements, such as energy efficiency in manufacturing or emissions from ICT usage, yet few offer a coherent evaluation of how digitalisation as a comprehensive process

influences environmental performance across various sectors and regions (Mouthaan et al. 2023).

A second gap relates to the spatial scale of analysis. A large share of the literature remains focused on the national level, neglecting regional or subnational evaluations that are essential for comprehending the implications of the twin transition.

Third, applied research has rarely investigated spatial dynamics and spillover effects. Environmental stresses and digital innovations transcend administrative boundaries. Emissions produced in one locale generally impact adjacent regions (Fang et al. 2015; Chen et al. 2017), but investments in digital infrastructure or technological capabilities can disseminate through the channels already mentioned. Traditional regression methods that assume independence among units are inadequate; therefore, spatial econometric models are more appropriate for addressing these interdependencies (Anselin 1988).

Finally, there exists a geographical disparity in empirical evidence. A significant portion of the current study is focused on a limited number of nations, notably China and the United States, whereas studies pertaining to Europe are very rare. The allocation of attention across European regions is inconsistent, with scant evidence for certain Southern economies. Italy exemplifies a pertinent case (Cartone et al. 2017): its geographical diversity, institutional fragmentation, and infrastructural disparities render it an especially significant context for examining the interplay between digitalisation and environmental outcomes; however, the volume of studies specifically focussing on the Italian context is limited, indicating opportunities for further exploration and comparative analysis.

1.3.3 Gaps in addressing regional heterogeneity

A major limitation in the existing literature is the insufficient attention to regional heterogeneity in the environmental effects of digitalisation. Numerous studies persist in examining these processes at the aggregate national level, implicitly presuming that the relationship between digitalisation and sustainability is uniform across regions. This assumption neglects the influence of local conditions

(economic frameworks, infrastructural resources, and institutional capabilities) on the relationship between digital adoption and environmental effects.

Another crucial element relates to the functional aspect of the relationship. A large amount of empirical research depicts the relationship between digitalisation and environmental performance as linear, indicating that gradual increases in digital intensity yield corresponding environmental impacts. Recent evidence indicates more intricate dynamics, including threshold or U-shaped relationships: initial stages of digital adoption may lead to increased emissions, whereas environmental advantages emerge only when complementary infrastructures, renewable energy resources, and human capital are adequately developed (Lei et al. 2023; Bai et al. 2023).

Addressing these gaps necessitates analytical frameworks that can encompass both non-linear trajectories and spatial diversity. Recognising that the environmental impacts of digitalisation vary by location will enable future research to produce more nuanced evidence and offer insights pertinent to policy formulation across diverse European areas.

1.4 Contributions and objectives of the thesis

The primary aim of this thesis is to evaluate the impact of digitalisation on environmental outcomes across various regions, focussing specifically on spatial dependence and regional heterogeneity. The dissemination of digital technology is frequently depicted as a catalyst for sustainability; nevertheless, the evidence is fragmented, and there is limited understanding of how these processes manifest in various territorial contexts. This study seeks to address that gap by employing a regional viewpoint and utilising methodologies that can capture spatial interdependencies and variations in local trajectories.

From a conceptual perspective, the thesis develops a territorial framework for interpreting the environmental impacts of digitalisation. By integrating concepts from the fields of innovation, economic geography, and environmental economics,

it conceptualises digitalisation not merely as a technological enhancement but as a process situated within spatially distinct systems of production, infrastructure, and governance. This concept facilitates the analysis of the twin transition by exploring the interaction of digital and environmental dynamics across different regional contexts, rather than as homogeneous worldwide trends. A thorough literature review further contributes by synthesising and organising existing knowledge regarding the environmental impacts of digitalisation. The review offers the conceptual framework for empirical investigations by categorising impacts beyond the basic positive/negative dichotomy and differentiating between various dimensions of digitalisation.

The empirical contribution is in the implementation of this approach within two complementary situations. The Italian case study examines the relationship between fibre-optic deployment and air quality at the provincial level (NUTS-3 units), offering one of the initial spatially explicit evaluations of digital infrastructure and environmental performance within a single nation. The EU-wide analysis broadens this viewpoint to NUTS-2 regions, examining the relationship between different dimensions of digitalisation (internet access and connection quality) and GHG emissions. Taken together, these studies provide comparative insights into the interaction between digitalisation and environmental effects across various territorial sizes.

Methodologically, the thesis integrates approaches rarely combined in this field. It employs spatial models to address spillovers and spatial dependence, spatially weighted regression to investigate variability in local interactions, and quantile regression to examine distributional impacts across the emissions spectrum. The work utilises the Bayesian Interpolation Method to impute missing regional data, using auxiliary factors while maintaining spatial integrity. The econometric study includes quadratic specifications and quantile regressions to identify non-linear and distributional heterogeneities, providing a more detailed understanding of the interaction between digitalisation and environmental effects.

Finally, the thesis presents a policy contribution by demonstrating how horizontal interventions produce varied environmental impacts based on regional conditions.

The findings underscore the potential for beneficial spillovers and the risk of unequal advantages, so guiding the formulation of policies that are attuned to spatial variation while maintaining coherence at national and EU levels.

1.5 Thesis structure

The remainder of this thesis is structured in four chapters. Chapter 2 offers a comprehensive review of the research regarding the environmental consequences of digitalisation. It combines bibliometric analysis with a systematic classification of fifty studies published from 2018 to 2023, providing an updated picture of the field. The chapter emphasises the ongoing presence of mixed and occasionally contradictory results, indicating that digitalisation can produce positive, negative, or complex environmental consequences, contingent upon the technology aspect or the geographical context. It emphasises the fragmented manner in which digitalisation has been assessed – spanning from network coverage to the adoption of advanced technologies – and highlights the lack of comparative, regionally nuanced methodologies capable of capturing these disparities.

Chapter 3 examines the Italian context, investigating the correlation between the deployment of fibre-optic broadband and air quality at the provincial level (NUTS-3 units). The chapter uses Italy's detailed spatial data to investigate both direct effects and interregional spillovers, applying approaches that explicitly account for spatial dependence. The findings indicate that digital diffusion can mitigate air pollution, with impacts reaching beyond the provinces of implementation and affecting adjacent regions, thereby indicating spatial spillovers. Moreover, mediation analysis demonstrates that decreases in fuel use are a primary mechanism facilitating these enhancements.

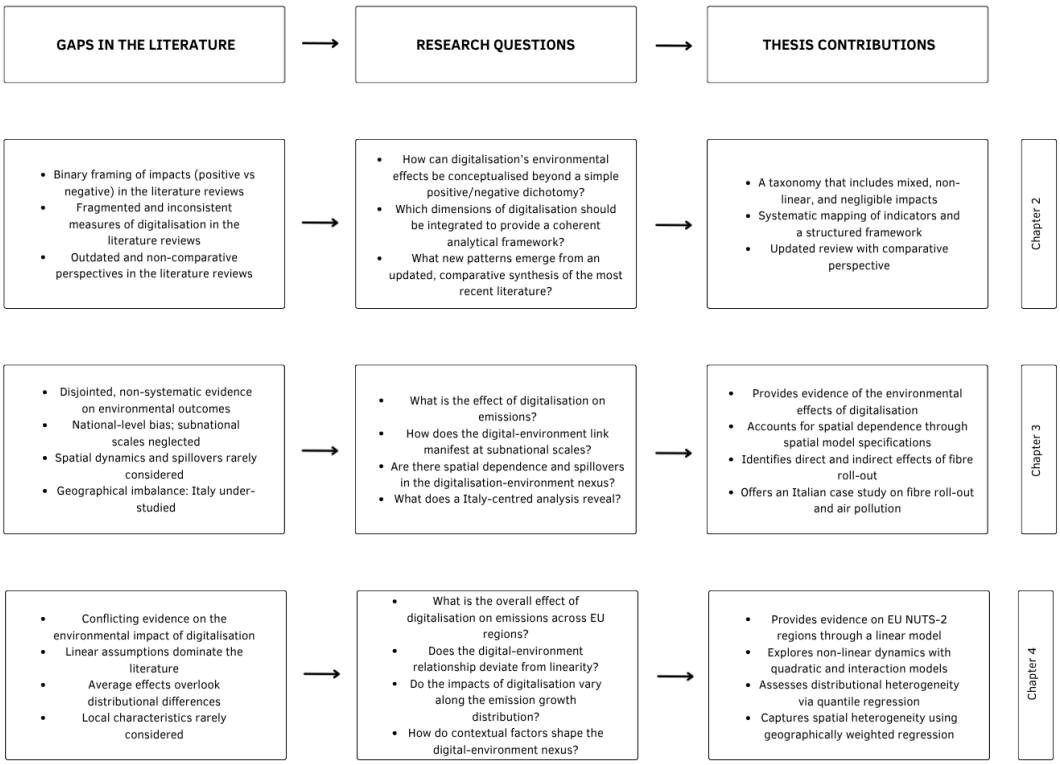
Chapter 4 extends the analysis to European NUTS-2 regions and enhances the conceptualisation of digitalisation by incorporating several measures of access and connection quality. The analysis examines two aspects of heterogeneity. Initially, it examines distributional heterogeneity, evaluating whether the effects of digitalisation differ throughout the emissions distribution i.e., between high-emission

and low-emission places. Finally, it analyses spatial heterogeneity, illustrating how the environmental impacts of digitalisation vary between regions with differing economic and infrastructural characteristics. This dual perspective underscores that the environmental consequences of digitalisation cannot be uniformly generalised across Europe but are influenced by the distinct characteristics of each geographical context.

Chapter 5 finally concludes by synthesising the findings across several scales, examining their implications for policy and future study concerning the territorial aspect of the twin transition.

To summarise the overall structure and logic of the thesis, Figure 1.1 presents the main literature gaps, corresponding research questions, and contributions.

Figure 1.1: Overview of the thesis framework: from literature gaps to research questions and contributions.



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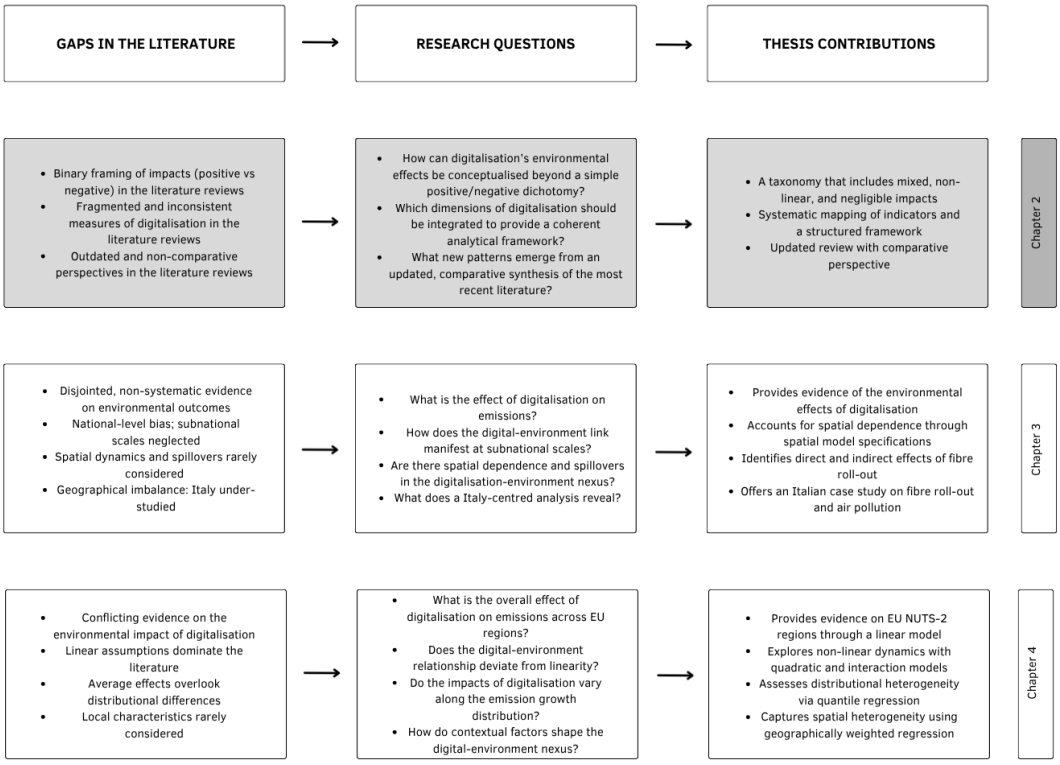
Chapter 2

Digitalisation and environmental implications: a systematic literature review of impacts and challenges

In the context of climate change and digital transformation, this study systematically reviews the environmental impacts of digitalisation, addressing its complexities and challenges. The review focuses on 50 papers published between 2018 and 2023, using bibliometric analysis and a hierarchical classification framework. Papers are classified into three macrogroups based on the environmental impacts of digitalisation: positive, negative, and complex impacts, which are further divided into subcategories based on digital dimensions such as diffusion, technology adoption, and other factors. The results show that most studies report complex or context-dependent impacts, followed by studies that highlight positive impacts, while a smaller number identify negative impacts.

Figure 2.1 highlights the section of the overall thesis framework that corresponds to Chapter 2, focusing on the literature review stage and its related contributions.

Figure 2.1: Position of Chapter 2 within the overall thesis framework.



2.1 Introduction

Climate change is one of the most pressing global challenges of our time. Driven by anthropogenic greenhouse gas emissions (GHG), it has already triggered widespread and severe consequences, including more frequent and intense extreme weather events. While immediate action to reduce emissions is critical, the inertia of the climate system means that some ongoing impacts are inevitable. This scenario highlights the importance of reducing GHG to mitigate further impacts on global warming and climate dynamics (European Commission 2023). In response to these challenges, the European Union has set a target to achieve climate neutrality by 2050 and launched the European Green Deal in 2019 (European Commission 2019) – an ambitious investment plan to promote sustainable growth. Among its key initiatives, the Green Deal emphasises the contribution of digital technologies to achieving climate neutrality, resource efficiency, and sustainable growth.

Information and communication technologies (ICT) have been identified as a key factor in reducing emissions. European Commission (2025) estimates that their use could reduce travel by 15-20% and GHG by 10-15%. However, the relationship between digitalisation and the environment is complex and not without contradictions. On the one hand, digital transformation is redefining business models, consumer behaviour and market dynamics towards more efficient resource use and dematerialisation. Within local production systems, digital transformation can reshape environmental and socio-economic dynamics by fostering synergies between manufacturing and knowledge-intensive services (Bellandi et al. 2020). On the other hand, several studies suggest that the early stages of the development of the digital economy may lead to an increase in CO_2 emissions, with potential reductions only occurring after a critical threshold of digitalisation is reached (Ahmadova et al. 2022; Zheng et al. 2023)

In this context, particular attention has been given to the so-called carbon rebound effect. This phenomenon occurs when the benefits associated with the adoption of digital technologies, such as reduced energy consumption, are offset by an overall increase in resource use, resulting in a net negative environmental impact (Wu et al. 2023; Peng et al. 2023; Lan and Zhu 2023). Challenges in the equitable adoption

of digital technologies across regions and sectors, as observed in policy frameworks like Italy's National Recovery and Resilience Plan (Bellandi et al. 2022), further complicate the assessment of their environmental impact. The literature thus presents different perspectives on the overall environmental impact of digitalisation, with results varying depending on the contexts analysed, the economic models considered, and the methodologies used.

Several literature reviews have explored the relationship between digitalisation and environmental impacts, adopting different approaches and analytical perspectives. Mouthaan et al. (2023) examine digitalisation as a General Purpose Technology and discuss its transformative potential for sustainability. They highlight that the literature often emphasises efficiency gains, overlooking unintended consequences. Charfeddine and Umlai (2023) provide a systematic review of studies published between 2000 and 2022 and show that the relationship between digitalisation and sustainability is often non-linear, with digital adoption initially increasing emissions before leading to efficiency improvements.

A different perspective is offered by Guandalini (2022), who performs a bibliometric analysis of 153 articles spanning over 20 years. She classifies the papers according to the topic they address, including "applicability to industries or sectors" and "digitalisation strategies for sustainability purposes". Xu et al. (2022) investigate the role of digitalisation in achieving the Sustainable Development Goals, emphasising the importance of governance structures and regulatory frameworks in ensuring environmental benefits.

While these reviews provide valuable insights into the relationship between digitalisation and environmental sustainability, they have some limitations that this study aims to address. Most of them classify the environmental impacts of digitalisation in binary terms, distinguishing between positive and negative impacts. Although some studies acknowledge that the relationship may be complex and context-dependent, they do not use a structured classification to account for such variability. In this study, we introduce a third category that recognises complex or insignificant effects, which better reflects the variability observed in the literature.

Another gap concerns the way in which different dimensions of digitalisation

are considered. While some studies distinguish between digital applications or sectoral effects, they do not adopt a consistent classification framework. This study distinguishes between digital intensity and diffusion, technology incorporation, and other digital dimensions, allowing for a more structured understanding of how digitalisation interacts with environmental sustainability.

Finally, this review provides an update and systematic analysis of 50 studies published between 2018 and 2023. By integrating a preliminary bibliometric analysis with a structured categorisation of articles, it provides a more comprehensive view of the heterogeneous environmental impacts of digitalisation, highlighting relevant trends and critical issues.

This study provides a basis for future research to investigate less explored aspects of the relationship between digitalisation and environmental sustainability. By highlighting the importance of accounting for technological, economic, and geographic specificities, it underscores the need for an approach that reflects the complexity of these interactions. Furthermore, this research acknowledges the influence of policy in shaping both the opportunities and challenges associated with sustainable digital transformation.

The remainder of the study is organised as follows. Section 2.2 describes the methodology used to analyse the research outputs, including a bibliometric analysis and the classification of articles. The results of the bibliometric analysis are presented in Section 2.3. Section 2.4 presents the results of the classification. Finally, the conclusions are presented in Section 2.5.

2.2 Methodology

The selection of articles for this review is guided by the criteria of relevance and timeliness, with the aim of capturing the rapid evolution of the digital sector and its growing impact on the environment and climate change.

Following Cronin et al. (2008), we approach the literature review process by first defining a clear topic of interest and identifying appropriate databases to search

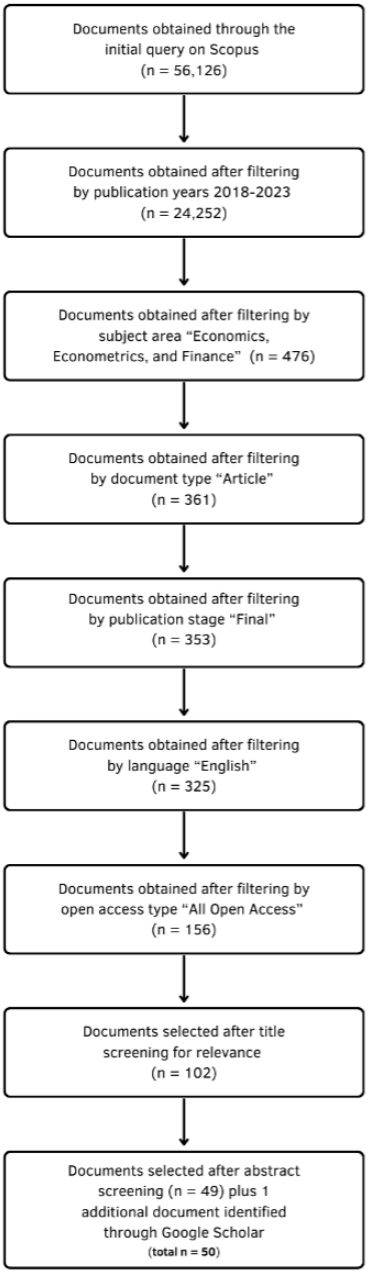
(i.e., Scopus and Google Scholar). As recommended, we develop a search query with keywords and Boolean operators to refine the results. In particular, the query targets the keywords of articles, combining terms related to digitalisation ("digit*", "ICT", "Information and communication technolog*") with those concerned with environmental issues ("environment*", "greenhouse ga*", "GHG", "carbon emission*"). Keywords within each group are linked using the "OR" operator to include alternatives, while the "AND" operator ensures that at least one term from each group is present. Truncation (e.g., "digit*") is used to capture variations such as "digital", "digitalisation" or "digitally" to ensure a comprehensive yet focused search.

To ensure a timely analysis, we consider studies published between 2018 and 2023. This timeframe follows the guidance of Cronin et al., who recommend choosing a period of 5-10 years to balance relevance and manageability. The starting point of 2018 is chosen because it marks the publication of the European Commission's Communication "A Clean Planet for All" (European Commission 2018), which highlights the role of digitalisation in supporting climate change and lays the groundwork for the European Green Deal announced in 2019. Studies from 2024 are excluded to avoid potential inconsistencies due to ongoing publication processes.

To refine selection, the subject area is limited to "Economics, Econometrics and Finance". Only peer-reviewed journal articles in English, final publications, and open access documents are included to ensure accessibility. In the next step, papers that are specifically focused on the field of finance are excluded based on their titles. Following Cronin et al., the abstracts of the remaining articles were reviewed to assess their alignment with the objectives of the study. This process results in the selection of 50 articles that address the intersection of digitalisation and environmental impact. A flowchart of the article selection process is shown in Figure 2.2[1]

[1]The data presented in the figure refer to results obtained from the Scopus database.

Figure 2.2: Paper selection process.



In the first phase of the analysis, we conduct a bibliometric analysis to identify key emerging trends in the selected literature. This analysis serves as a tool to assess the impact of the articles within the field and to uncover prevailing patterns.

Specifically, the bibliometric analysis examines three main aspects: the temporal distribution of articles by year of publication, the most frequently cited academic sources, and recurring keywords in the selected studies. While the exclusion of articles not indexed in Scopus limits the use of the R package "Bibliometrix" (Aria and Cuccurullo 2017), we adapt its framework to design a targeted systematic analysis. This approach allows us to characterise the selected studies and better understand the dynamics within the research field.

In the second phase, the articles are classified into three primary macrocategories based on the environmental impacts attributed to digitalisation. This classification is made by combining an analysis of the quantitative results reported in the studies with the qualitative assessments provided in the authors' conclusions. The first macrocategory includes studies that highlight positive environmental impacts, such as reduced GHG or improved environmental quality, directly related to the adoption of digital technologies. For example, some papers discuss how digital solutions – such as smart grids or remote working - can reduce emissions by optimising energy consumption or reducing the need for transport (Shehzad et al. 2022; Chien et al. 2021).

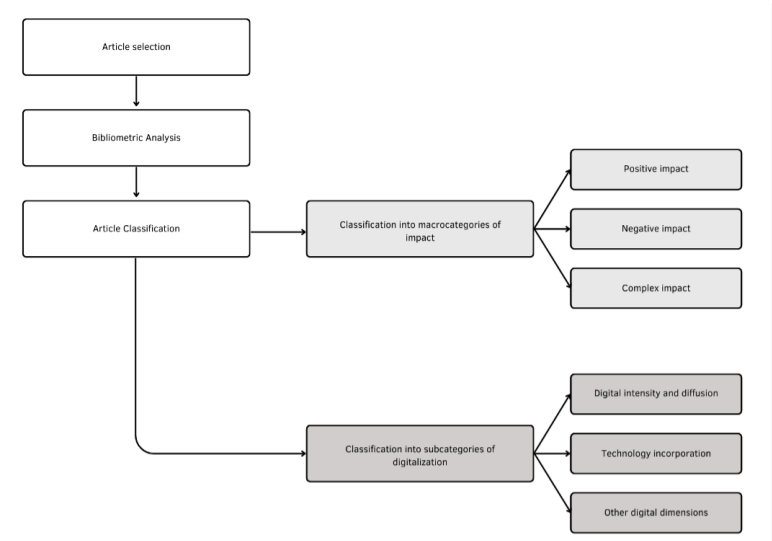
The second category includes studies that report negative environmental impacts associated with increased energy demand from digital infrastructure, production and disposal of electronic equipment, and rebound effects where initial benefits are offset by increased overall resource use. Examples include the environmental costs associated with the expansion of data centres or the growing problem of e-waste (Park et al. 2018; Charfeddine and Kahia 2021).

The third macrocategory includes studies that present complex, non-linear, or context-dependent results. These include cases where the impact of digitalisation varies depending on external factors such as technological maturity, local policies, or economic conditions. Some studies find no significant correlation between digitalisation and environmental outcomes, while others report results that cannot be clearly classified as positive or negative (Sinha 2018; Amri et al. 2019; Ben Lahouel et al. 2024).

To deepen the analysis, we further divide the studies into subcategories based on

the specific dimensions of digitalisation addressed. The first subcategory focuses on the technological infrastructure, adoption, and use of ICT, emphasising the intensity and diffusion of these technologies. The second subcategory includes articles that analyse the environmental impact of incorporating digital technologies into firms, covering aspects such as digital inputs and outputs, the use of industrial robotics, and the transformation of ICT sectors. Finally, the third subcategory examines other dimensions of digitalisation, such as digital technology patents and ICT goods imports, which are not directly covered by the previous categories. Each article is classified under only one of the three primary macrocategories, but can be associated with several subcategories depending on the specific focus of the analysis. Figure 2.3 shows the flowchart outlining the stages of our analysis.

Figure 2.3: Steps in the paper analysis process.



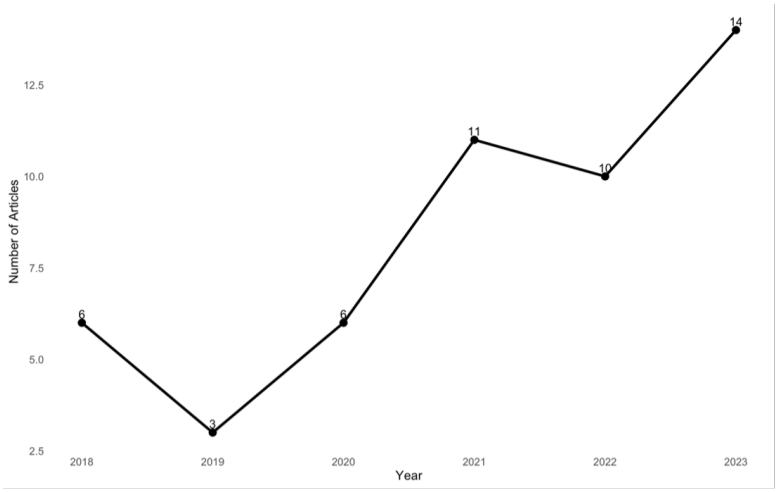
This systematic and hierarchical classification framework enables a clear and detailed outline of not only the heterogeneous impacts of digitalisation on the environment, but also the different dimensions that define the phenomenon. Such an approach provides an integrated understanding of emerging trends and critical challenges related to the interaction between digital technologies and the environment.

2.3 Results of bibliometric analysis

The bibliometric analysis is conducted to identify key trends in the selected literature, to provide an overview of scientific progress in the field and to highlight emerging dynamics. The first aspect examined is the temporal distribution of publications, which reflects the evolution of academic interest in the relationship between digitalisation and its environmental impact.

In recent years, there has been an evident increase in the number of articles published, as shown in Figure 2.4. In both 2018 and 2020, six articles were recorded, while in 2019 there was a decrease to three publications. Beginning in 2021, there was an increase with eleven articles published, followed by ten in 2022 and a peak of fourteen articles in 2023. This rising trend, represented by the line in Figure 2.4, highlights the growing academic focus on the nexus between digital technologies and environmental sustainability. This shift is likely driven by the introduction of global policies, such as the European Green Deal, and the urgency of addressing climate change.

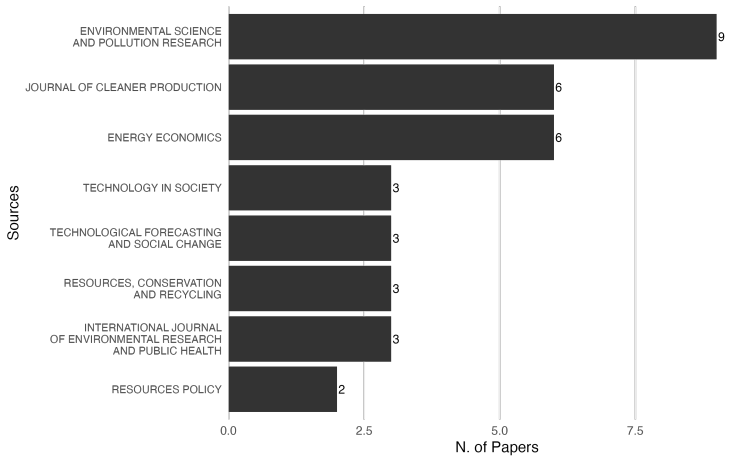
Figure 2.4: Annual distribution of papers in selected literature (2018-2023).



Another important finding is the identification of the most active academic sources in this area, which confirms the multidisciplinary nature of the topic. As shown in Figure 2.5, the most prominent journal is Environmental Science and Pollution

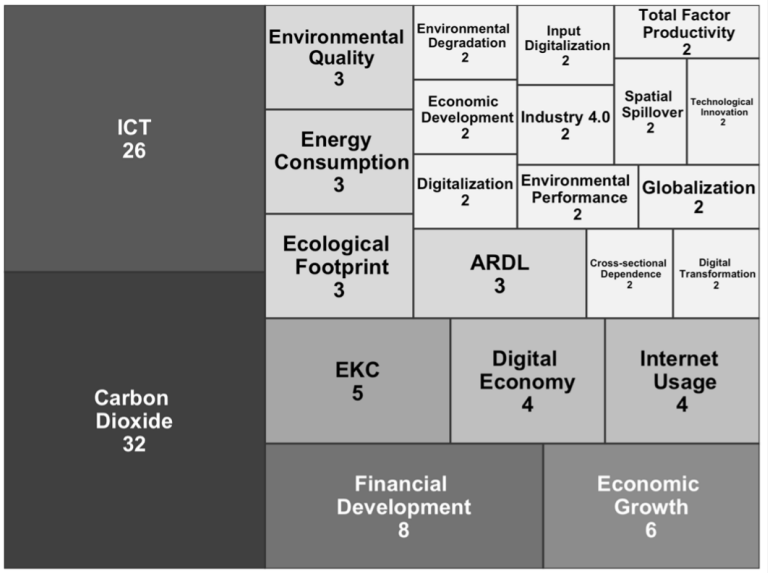
Research with nine papers, followed by the Journal of Cleaner Production and Energy Economics with six papers each. These journals serve as primary outlets for studies that integrate environmental, economic, and technological perspectives. Other sources, although less represented, highlight the cross-disciplinary nature of the topic, involving fields such as economics, engineering, and social sciences.

Figure 2.5: Top academic sources in selected literature.



Finally, keyword analysis provided insights into the main themes addressed in the selected literature. The tree map in Figure 2.6 shows that the most common terms are "carbon dioxide" (32 occurrences) and "ICT" (26 occurrences), which is consistent with the focus of the reviewed articles. Beyond these central terms, other keywords reflect the complexity and multi-dimensionality of the topic. Terms such as "financial development" (8 occurrences) and "economic growth" (6 occurrences) indicate a growing interest in the links between digitalisation, economic growth, and sustainability. Similarly, terms such as "energy consumption" and "ecological footprint" highlight a focus on specific environmental impacts, such as the energy consumption associated with the adoption of digital technologies and the pressure on ecosystems. These terms suggest that the literature is moving beyond GHG to encompass a broader range of relevant environmental indicators.

Figure 2.6: Tree map of keywords in selected literature.



2.4 Results of article classification

To examine the relationships between the dimensions of digitalisation discussed in the articles and the environmental impacts identified in the 50 selected studies, we use a grouped bar chart (Figure 2.7). This visual representation is chosen to clearly show the distribution of articles across the defined macrocategories – "positive impact", "negative impact", and "complex impact" – and the associated subcategories – "digital intensity and diffusion", "technology adoption", and "other".

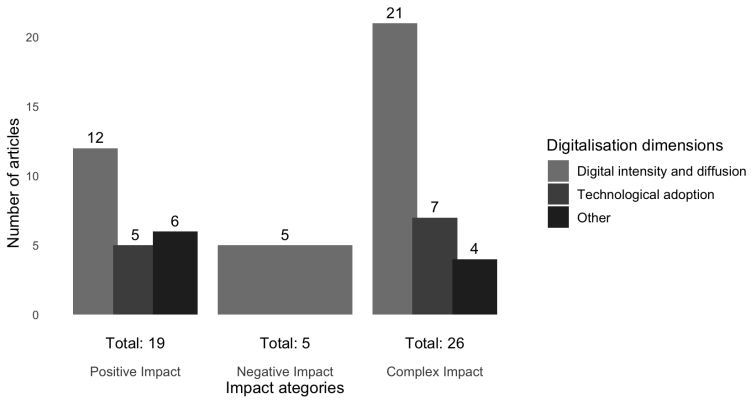
As shown in Figure 2.7, most articles focus on the complex impacts of digitalisation on the environment (25 articles), followed by those reporting positive impacts (20 articles). Studies documenting negative impacts are fewer, with only 5 articles. In terms of subcategories, "digital intensity and diffusion" is the most explored dimension, especially within the positive and complex impact categories, while "other" and "technology adoption" are less frequently addressed. An interesting observation is the presence of articles classified under multiple subcategories within the same macrocategory. For example, in the macrocategory "Complex Impacts", two articles are simultaneously classified under "Digital Intensity and Diffusion",

"Technological Adoption", and "Other". This reflects the idea that some studies examine dimensions of digitalisation that are not easily clearly distinguishable, but rather interact in complex ways to shape the observed impacts. The overlap between subcategories within the macrocategory "Complex Impacts" highlights the multifaceted and multi-dimensional nature of these studies, which consider multiple aspects of digitalisation to explain its environmental impacts.

Papers reporting negative impacts focus exclusively on the "digital intensity and diffusion" dimension. This finding may indicate that, in certain contexts, the spread of digital technologies may lead to unintended environmental consequences. In contrast, articles reporting positive or complex impacts show greater diversity across subcategories. This suggests that the analyses in these cases consider a broader range of factors and dimensions of digitalisation, exploring the multiple ways in which these technologies affect different aspects of environmental sustainability.

In the following sections, we discuss the main characteristics and conclusions of the articles analysed. The discussion is structured according to the macrocategories of environmental impact identified in the articles. Each macrocategory is further subdivided into sections dedicated to the different dimensions of digitalisation, reflecting the subcategories identified during the classification process. The first section examines studies documenting positive impacts, highlighting evidence related to the use of digital technologies to improve environmental quality. The second section will analyse articles reporting negative impacts of digitalisation, with a focus on identified risks. Finally, the third section will address studies that present complex impacts, highlighting the interconnections and uncertainties observed in the literature.

Figure 2.7: Grouped bar chart of article classification by environmental impact and digitalisation dimensions.



2.4.1 Positive environmental impacts of digital technologies

The literature examining the positive environmental impacts of digital technologies covers a wide range of approaches and topics. Some studies focus on the use and diffusion of digital technologies, examining aspects such as internet access, broadband usage, and ICT technologies more broadly, including mobile telephony and other infrastructures. Other studies focus on industrial digitalisation, analysing phenomena such as the integration of digital inputs, automation and the use of industrial robotics. Still other studies examine less common dimensions of digitalisation, such as the import and export of ICT goods or the role of digital finance in the adoption of sustainable technologies. A segment of the literature takes an integrated approach, examining the use and diffusion of digital infrastructure, industrial digitalisation, and other dimensions together to provide a comprehensive view of the positive environmental impacts of digital technologies. Each of these thematic areas is discussed in detail in this section, with particular emphasis on studies that address multiple aspects simultaneously, with references provided where relevant.

Positive environmental impacts of digital intensity and diffusion

Several studies highlight transport as a crucial factor in the relationship between ICT technologies and the reduction of CO_2 emissions. Briglauer et al. (2023), analysing 34 OECD countries, show that factors such as broadband, 3G coverage and ICT goods trade reduce the need for physical transport through teleworking, e-learning and e-health solutions. In particular, broadband and fibre optics are shown to significantly reduce travel, leading to significant emissions reductions. Haseeb et al. (2019), studying BRICS countries from 1994 to 2014, confirm that internet and mobile phone use reduce CO_2 emissions, while other factors such as energy consumption and globalisation have the opposite effect. Chatti (2020), focusing on road freight transport in 43 countries, finds that the use of ICT improves operational efficiency and reduces emissions by 1.59% to 2.26%, depending on the technology used.

Some studies also examine the relationship between economic development and pollution using the Environmental Kuznets Curve (EKC), which posits an inverted U-shaped relationship between economic growth and environmental degradation. Caglar et al. (2021) examine 10 countries with high environmental impacts and reject the EKC hypothesis, showing that ICT, renewable energy, and financial development are more effective in reducing ecological footprints than GDP growth alone. Conversely, Chien et al. (2021) confirm the EKC hypothesis in BRICS countries, finding that internet use reduces CO_2 emissions, while economic growth and financial development increase them. Quaglione et al. (2023) highlight the significant role of both fixed and mobile broadband in reducing CO_2 emissions, with fixed broadband having a more pronounced effect in both low- and high-income contexts. They also find a non-linear relationship between GDP per capita, its square, and emissions, supporting the EKC hypothesis.

Another approach in the literature is to use composite indicators to represent ICT technologies. Ahmed et al. (2021) develop an indicator that combines four factors: internet users, mobile phone subscriptions, fixed phone subscriptions, and fixed broadband subscriptions. They find that digitalisation and globalisation reduce CO_2 emissions, while urbanisation, economic growth, and human capital

development increase emissions. Wu et al. (2023) create a digital economy index that focuses only on internet-related aspects, such as internet penetration, the number of connected professionals, and mobile internet users. They analyse how the integration of the digital economy into China's manufacturing industries (labour-intensive, capital-intensive, and technology-intensive) affects carbon emissions. Their results suggest that the digital economy reduces emissions, with the largest effects in technology-intensive industries, where structural improvements lead to efficiency gains. Li and Liao (2022) take a broader approach, examining the impact of digital technologies on environmental progress in China using a composite indicator of urban technological development. This includes digital infrastructure (broadband and mobile phone penetration rates), digital factor input, digital factor output, and a digital financial inclusion index. Their study shows that digital development reduces emissions locally and in surrounding cities, with the spatial impact diminishing after a certain distance.

Several studies assess the impact of digitalisation on carbon emissions in China, often using spatial approaches to evaluate impacts at the city, provincial, or regional level. Du et al. (2023) examine how digital infrastructure construction improves carbon emission efficiency and promotes environmental awareness and innovation. Their results highlight benefits not only locally, but also in neighbouring areas, thanks to knowledge diffusion and the reduction of geographical and administrative barriers. Sun and Kim (2021), on the other hand, examine the impact of the ICT industry in Chinese provinces using monetary indicators (ICT capital and industrial output value) and non-monetary indicators (internet penetration). They find that monetary indicators have a stronger impact, especially in developed regions, but also note that ICT technologies can exacerbate regional disparities in carbon intensity. Lu (2018) analyses 12 countries, including China, Brazil, and Germany, and finds that a 1 per cent increase in internet users reduces CO_2 emissions by 0.06 per cent, while factors such as energy consumption and financial development contribute to higher emissions.

Positive environmental impacts of technology incorporation

The literature on industrial digitalisation often focuses on its impact on Green Total Factor Productivity (GTFP), a measure that combines production efficiency with environmental resource use and carbon emissions. Li and Liao (2022) analyse how input digitalisation affects GTFP and show that it significantly improves low-carbon productivity by reducing operating costs and replacing energy-intensive resources with more efficient alternatives. This positive effect is most pronounced in middle-income countries and in the manufacturing and services sectors, while it is not significant in agriculture. The authors identify energy efficiency and labour productivity as the main mechanisms through which digitalisation affects GTFP.

Wen et al. (2021) examine the impact of industrial digitalisation on the environmental performance of Chinese manufacturing firms using two indicators: the ratio of ICT capital to industrial value added and the ratio of ICT services to intermediate inputs. Their results suggest that digitalisation improves environmental performance, especially in highly polluting and less capital-intensive industries. Wen et al. identify two main mechanisms: the structural effect, which reduces the scale of production of more polluting firms through increased ICT capital and services, and the technological effect, which promotes product innovation and increases GTFP.

Wang et al. (2022b) examine the impact of industrial robots on energy efficiency in the manufacturing sector, using a study of 38 countries and 17 sectors from 2000 to 2014. Their results show that robots reduce the energy intensity of manufacturing by improving efficiency through technological progress and complementary technological effects, rather than by directly increasing labour productivity.

Studies by Liu et al. (2022) and Sun and Kim (2021) are also relevant to this category. Liu et al. construct a composite indicator of digital technological development that includes both digital inputs, calculated on the basis of the share of information sector workers and R&D expenditures relative to GDP, and digital outputs, measured by per capita telecommunications revenues. Sun and Kim, on the other hand, use a monetary proxy based on ICT capital and the value of gross industrial production to assess the environmental impact of the ICT industry.

Positive environmental impacts of other digital dimensions

Shehzad et al. (2022) validate the EKC hypothesis in Pakistan and show that ICT, as measured by a communication technology index, contributes to the reduction of CO_2 emissions. This is achieved through the adoption of smart technologies such as smart grids and smart appliances, as well as innovations in sectors such as online banking and digital shopping. Nguyen et al. (2020), analysing G20 countries between 2000 and 2014, highlight that the import of advanced ICT technologies and innovations, particularly in the energy sector, increases productivity and mitigates environmental degradation. Both studies confirm that, consistent with the EKC, economic growth initially increases emissions but leads to reductions in the long run. Similarly, Briglauer et al. (2023) include ICT imports and exports among the key factors in assessing the environmental impact of digital technologies, noting their role in mitigating climate change.

Zhou and Liu (2023) examine the impact of digitalisation on resource efficiency and the achievement of environmental, social, and governance goals. Analysing 450 listed companies in G20 countries, they find that increased ICT spending promotes investment in environmental, social, and governance sustainability, while higher energy spending hinders such progress. Yang et al. (2023) examine the carbon emission intensity of Chinese manufacturing firms using a text mining approach applied to corporate reports. Their findings suggest that digitalisation reduces emission intensity through mechanisms such as green technological innovation, alleviation of financial constraints, and reduced information asymmetry.

Finally, the study by Li and Liao (2022), previously noted for its composite indicator of digital development, is relevant in this category for its use of the digital financial inclusion index. This highlights a positive spillover effect of digital progress on carbon emission reductions.

2.4.2 Negative environmental impacts of digital technologies

This section examines five studies that highlight the deterioration of environmental quality as a consequence of digitalisation. The articles analysed focus on the environmental impacts of the increasing diffusion and use of ICT technologies, emphasising the challenges posed by technological advances and the need for mitigation strategies to balance technological progress with environmental sustainability.
It is noteworthy that, among the studies selected for this review, those documenting negative impacts exclusively analyse variables related to digital intensity and diffusion. No studies were identified that address negative impacts related to the other two subcategories of digitalisation, namely technology incorporation and other digital dimensions. In addition, these research studies often use the same variables as the studies reporting positive impacts. This suggests that differences in findings may be primarily due to the sample of countries analysed or the methodologies used, rather than the inherent nature of the variables themselves.

Negative environmental impacts of digital intensity and diffusion

The negative environmental impacts of digitalisation are often attributed to the increased energy consumption required by ICT infrastructures, resulting in higher CO_2 emissions (the so-called carbon rebound effect). Studies by Avom et al. (2020) and Atsu et al. (2021), focusing on sub-Saharan Africa, find that the spread of ICT – measured by internet and mobile phone use in the first study and fixed-line telephony in the second – contributes to an increase in emissions. This effect is primarily related to the increased energy demand for operating digital infrastructure. Their findings suggest that the energy intensity associated with ICT use in contexts with limited access to sustainable energy sources plays a key role.

Charfeddine and Kahia (2021), focusing on MENA countries, reach similar conclusions, showing that increased ICT use is associated with greater environmental degradation. This finding is attributed to the energy dependence of digital in-

frastructures, which in these contexts are predominantly based on non-renewable energy sources. Despite their different geographical scope, these studies converge on the idea that ICT can have negative environmental effects if they are not combined with strategies to improve energy efficiency and promote the use of renewable energy. Park et al. (2018) analyse European Union countries and show that the use of internet and ICT technologies, while essential for economic and social development, contributes to higher energy consumption and CO_2 emissions. This effect is exacerbated by the reliance on non-renewable energy sources, with significant consequences for environmental quality. Similarly, Arshad et al. (2020), focusing on South and Southeast Asian economies, confirm that ICT technologies and energy consumption have a negative impact on carbon emissions, suggesting that in many countries ICT adoption has not been accompanied by significant improvements in energy efficiency. Collectively, these studies show that the environmental impact of ICT depends not only on technology adoption, but also on the energy context in which these technologies are implemented. Without the simultaneous development of sustainable energy infrastructures and targeted efficiency policies, ICT diffusion risks exacerbating environmental challenges. This underscores the urgency of an integrated approach that balances digital progress with sustainability.

2.4.3 Complex or insignificant environmental impacts of digital technologies

The final category includes twenty-five studies that highlight non-linear, context-dependent, or non-significant impacts of digitalisation on environmental quality. This section is divided again into three parts: the first focuses on the intensity and diffusion of digital technologies, the second examines the role of digital technologies in industry and their impact on the environment, and the third explores digital dimensions not covered in the previous categories, such as digital finance. Many of these studies use variables similar to those analysed in the previous categories. However, the differences in results are often due to factors such as the level of detail in the analysis or variations in the construction of composite indicators.

These discrepancies underscore the complexity of interpreting the environmental impacts of digitalisation and the need to consider a wide range of factors for a more accurate understanding.

Complex or non-significant effects of digital intensity and diffusion

The relationship between digitalisation and the environment is often characterised by complex dynamics, including non-linear effects and critical thresholds. Several studies emphasise that the environmental impacts of ICT vary significantly depending on the level of technological development, innovative capacity, and geographical context. Lahouel et al. (2021), focusing on Tunisia, analyse the environmental impact of digitalisation using indicators such as mobile and fixed line penetration. Their results reveal a threshold effect, where ICT start to contribute positively to CO_2 mitigation only after a certain level of technological diffusion has been reached. This is consistent with the idea that ICT act as a transmission channel, improving carbon efficiency and promoting low-carbon development. Building on this, Lahouel et al. (2022) extend the analysis to the MENA region and include additional explanatory variables such as energy consumption and trade openness. They confirm a non-linear relationship between ICT and CO_2 emissions, with ICT contributing significantly to emission reductions at high levels of diffusion. However, they also show that foreign direct investment and energy consumption can offset these environmental benefits, especially in regions with high ICT penetration. Similarly, Asongu et al. (2018), who study African countries, identify a threshold effect, where the positive environmental impacts of ICT emerge only after technological adoption reaches a minimum level of energy efficiency. This highlights the importance of policies that promote green infrastructure and efficient technologies to amplify the environmental benefits of digitalisation.

Several studies focus on Chinese cities to explore the relationship between digitalisation and the environment. Cheng et al. (2023) identify a technological and industrial threshold effect, showing that emission reductions require not only the adoption of digital technologies, but also green innovations and the restructuring of traditional industrial sectors. Using indicators such as internet penetration

and urban technology adoption, Sun et al. (2023) identify an inverted U-shaped relationship: the initial expansion of digitalisation increases emissions due to higher energy consumption, but beyond a certain threshold of digital development, technological efficiency leads to significant emission reductions. Similarly, Li and Wang (2022), combining spatial approaches with digital economy analysis, confirm the inverted U-shaped relationship and identify thresholds related to innovation capacity and industrial structure.

Barış-Tüzemen et al. (2020), analysing Turkey, find an inverted N-shaped relationship between ICT and pollution. Their study shows that while initial ICT adoption reduces emissions, extremely high levels of digitalisation can lead to rebound effects that increase carbon emissions again. These findings underscore the need to balance digital expansion with targeted policies for sustainable resource management.

The environmental impacts of digitalisation could vary significantly depending on geographic and socioeconomic contexts. Usman et al. (2021), who analyse countries with different levels of economic development, use indicators such as internet and mobile phone penetration. Their study finds that in high-income countries, ICT helps reduce emissions through infrastructure efficiency, while in low-income countries, where energy sources are predominantly non-renewable, digitalisation increases emission intensity. Albaity and Awad (2023), focusing on MENA countries, report similar results, analysing the impact of broadband and mobile telephony on carbon emissions. The positive effect of digitalisation appears only in countries with more advanced infrastructure and higher technological penetration, while in less developed contexts digitalisation tends to worsen environmental conditions, highlighting the need for policies to improve energy efficiency.

Khan et al. (2020) examine the relationship between ICT investment, mobile telephony, and carbon emission intensity. They also find that environmental benefits are only realised in countries with high levels of technological and financial development. In less developed countries, the expansion of digital technology tends to increase emissions, highlighting the need for infrastructure improvements. Lee et al. (2023), through a global comparative analysis focusing on the internet

and mobile telephony, show that in developed countries ICT have a positive environmental impact, while in developing countries digitalisation is associated with increased emissions due to energy inefficiency and lack of appropriate policies.

Sinha (2018) employs a composite indicator that combines internet, mobile telephony, and ICT investments. The results show that the impact varies widely within the group: in countries with a high share of renewable energy and efficient infrastructure, digitalisation reduces emissions, while in less advanced contexts it has a negative impact. Wang et al. (2022a) focus on Asian countries and show that the impact of ICT on emissions is strongly influenced by the level of innovation and the availability of renewable energy. In contexts with strong technological innovation, ICT adoption reduces emissions, while in less advanced countries, negative effects predominate.

N'dri et al. (2021) analyse the role of ICT in sub-Saharan Africa, highlighting how the impact depends on the institutional context and technological capacity. In countries with stronger institutional systems, ICT adoption can improve environmental sustainability, while in countries with limited resources or inefficient infrastructure, the effect is often negative, mainly due to dependence on fossil fuel energy. Kopp et al. (2023), looking at a global sample, show that the effect of digitalisation is positive only in the presence of a robust technological infrastructure and efficient environmental policies. In countries with low technological and financial development, digitalisation tends to increase emissions due to energy inefficiency and lack of access to renewable energy sources.

The impact on CO_2 emissions can also be influenced by interactions with economic factors, leading to different results depending on the context analysed. Danish et al. (2018), analysing 25 emerging economies, find that internet access, together with economic growth, can moderate the increase in carbon emissions. However, they emphasise that the effectiveness of this interaction depends on the quality of energy infrastructure and the presence of effective environmental policies. Yahyaoui (2024), focusing on Tunisia and Morocco, observes that the interaction between ICT and economic growth produces opposite effects: while the adoption of digital technologies is associated with increased emissions in the short term, it can

lead to reductions in the long term, especially when supported by policies that promote sustainable technologies. Similarly, Tsaurai and Chimbo (2019), who study emerging economies, focus on the combined effect of ICT and financial development. Their findings suggest that while ICT alone tends to increase emissions, its integration with a robust financial system can mitigate negative environmental impacts, highlighting the importance of synergies between financial and technological policies.

Not all studies find a significant relationship between digitalisation and environmental quality, suggesting that the impact of ICT may be neutral in certain contexts. Amri (2018) finds that ICT adoption does not have a significant impact on environmental quality, highlighting that digitalisation may not improve environmental conditions if it is not accompanied by targeted strategies. Amri et al. (2019), in a similar analysis for Tunisia using time series data, find no significant impact of ICT on CO_2 emissions. The authors attribute this neutrality to the lack of policies to promote a more sustainable use of digital technologies. Finally, Awad (2022) examines 47 sub-Saharan African countries using the Ecological Footprint as an indicator. The study finds no evidence of a significant impact of ICT on the environment, suggesting that institutional contexts and the adoption of renewable energy have a greater impact than digitalisation.

Complex or non-significant effects of technology incorporation

The incorporation of digital technologies in the manufacturing sector produces different environmental outcomes, reflecting the specific contexts analysed and the methods of digital technology adoption. Focusing on China, Tang et al. (2023) distinguish between productive and distributive digitalisation, finding that the latter can contribute to increased emissions. This is mainly due to the expansion of logistics activities, while the impact of productive digitalisation is less clear. Sun (2022) examines the link between industrial digitalisation and environmental policies, finding that the effectiveness of digital technologies in improving environmental quality depends on the existence of adequate local regulations and the integration of sustainable technologies. In the absence of these

conditions, the impact of digitalisation appears to be limited or insignificant. Wang and Guo (2023) examine the impact of digital technologies on energy efficiency, highlighting that the environmental impact is often neutral in less innovative firms. Technology adoption alone proves insufficient to achieve significant emission reductions without structural reforms in production processes.

Chiarini (2021) investigates the environmental performance of Italian manufacturing firms that have adopted Industry 4.0 technologies, including artificial intelligence, smart sensors, and additive manufacturing. The study shows that not all digital technologies improve environmental performance in the same way. While some technologies, such as data analytics, have a clear positive impact by optimising resource use, others, such as augmented reality, do not show a significant contribution to emissions reduction. This underscores the importance of aligning technology adoption with specific environmental goals to achieve meaningful results.

Li and Wang (2022), Cheng et al. (2023), and Wang et al. (2022a) – already discussed in the section on digital intensity and diffusion – also examine technology adoption in the industrial sector. Li and Wang find a non-linear relationship in which initial technology adoption increases emissions but later reduces them through improved energy efficiency. Cheng et al. emphasise that the environmental impact of digitalisation is influenced by industrial transformation and technological innovation. Wang et al. link the use of advanced technologies to improvements in energy efficiency, with environmental benefits emerging in highly innovative contexts.

Complex or non-significant effects of other digital dimensions

Bianchini et al. (2023) analyse the interplay between digitalisation and green technologies, focusing on the European context. Their study uses data on digital and environmental patents as well as GHG from highly polluting plants to assess the impact of the so-called 'twin transitions'. The results show a complex effect: digital technologies increase emissions due to their high energy requirements, while green technologies reduce emissions. However, the interaction between these two

transitions shows that the presence of green technologies can mitigate the negative impacts of digitalisation, suggesting that policies need to address these dimensions together to maximise environmental benefits.

The studies by Li and Wang (2022) and Wang et al. (2022a), discussed earlier, are also relevant here because they include the digital finance dimension. These studies show non-linear results, with the impact of digital technologies on emissions appearing neutral or insignificant in certain contexts. This effect is particularly evident in regions with low levels of technological innovation or where environmental policies are insufficient to fully exploit the benefits of digital technologies.

Sinha (2018) examines OECD countries and considers a combination of digital dimensions, including fixed broadband subscriptions, internet users, and exports of ICT goods and services. The study finds that the impact of ICT's exports on environmental quality depends on the level of technological development and the availability of sustainable energy infrastructure. In many cases, the direct impact on emissions is insignificant, highlighting the need for targeted policies that take into account local specificities to harness the potential of the digital dimension in the transition to sustainability. These studies confirm the complexity of the environmental impacts of digital dimensions and highlight the importance of specific contexts and integrated approaches for accurate assessments.

2.5 Conclusions

The purpose of this study was to analyse the relationship between digitalisation and environmental sustainability, an issue of growing importance considering the global challenges posed by climate change. The research addressed the inconsistencies highlighted in the literature: while digital technologies can help reduce GHG, their overall environmental impact depends on multiple factors, including the level of technological innovation, the institutional context, and local economic characteristics.

To address these uncertainties, we adopted a systematic approach and analysed

50 articles published between 2018 and 2023. The methodology included two main phases. First, a bibliometric analysis identified the main trends in the selected literature, revealing a growing academic interest in the topic and a marked multidisciplinarity, with contributions from fields such as economics, engineering, and environmental sciences. The keyword analysis further confirmed the complexity of the topic, showing how the interaction between digitalisation and the environment is approached from different perspectives, including not only CO_2 emissions, but also energy consumption, technological innovation and social sustainability. Second, the articles were classified into three main macrocategories: positive, negative, and complex impacts, each of which was further subdivided according to the dimensions of digitalisation analysed: digital intensity and diffusion, technological incorporation, and other dimensions.

The adoption of digital technologies is a tool to address environmental challenges and facilitate the transition to a more sustainable economic model. But the potential of ICT to reduce emissions and improve energy efficiency does not come automatically. It requires a well-structured policy framework to guide technological innovation towards clear environmental goals. The review findings indicate that in advanced contexts, the expansion of digital infrastructure has had a significant positive impact, reducing CO_2 emissions and promoting more efficient production models. However, these benefits can be further enhanced by policies that incentivise the adoption of renewable energy and the large-scale deployment of green technologies (Briglauer et al. 2023; Wang et al. 2022b).

In emerging economies, digitalisation represents both a challenge and an opportunity. On the one hand, ICT can act as a catalyst for sustainable economic development; on the other hand, the lack of an appropriate policy framework can limit these benefits or amplify negative effects, such as increased energy consumption. Regulatory measures – e.g. controlling the import of energy-intensive ICT equipment and promoting the local production of sustainable technologies – could align digital progress with global environmental targets (Avom et al. 2020; Du et al. 2023).

In the industrial sector, digital technologies (e.g. industrial robotics) represent a

case of innovation capable of transforming traditionally energy-intensive sectors. Nevertheless, the effectiveness of such innovations depends on the existence of strategic policies that promote the adoption of technological solutions in sectors with the greatest potential for emission reductions (Wang et al. 2022a). Furthermore, the progress of digitalisation requires constant monitoring to ensure that the benefits of ICT are not neutralised by side effects, such as increased energy demand or issues related to the disposal of obsolete technologies. An integrated policy approach, based on international cooperation and supported by structured economic incentives, could accelerate the diffusion of advanced technological solutions while reducing inequalities in access to innovation (Sun et al. 2023; Barış-Tüzemen et al. 2020).

In summary, the findings of this study confirm the heterogeneity of the environmental impacts of digital technologies and highlight the need for a contextual approach to assess their contribution to sustainability. While positive effects often predominate, there are situations where the impact is negative or neutral, particularly in the absence of adequate environmental policies or efficient technological infrastructures. To maximise the benefits of digitalisation, it is essential to integrate technological and environmental policies, promoting not only the adoption of ICT, but also the transition to renewable energy sources and sustainable innovation models. Future research should extend the analysis to less explored geographical contexts and delve deeper into long-term effects, providing a stronger empirical basis to guide policies and interventions towards a sustainable digital transition.

Our analysis suggests several opportunities for further research. A promising avenue involves examining the differential impact of digitalisation in specific geographic and sectoral contexts. Understanding how variables – such as technological infrastructures, local policies, and levels of economic development – influence the effectiveness of digital technologies in reducing environmental impacts could provide insights for targeted interventions.

Another important area for future research concerns emerging technologies, e.g. Internet of Things and Artificial Intelligence. These technologies have significant potential to transform environmental and economic dynamics, but require further

study, particularly in terms of their alignment with evolving regulatory frameworks. Greater attention to these aspects could help identify how digital innovations can be used to achieve environmental objectives while mitigating potential negative impacts.

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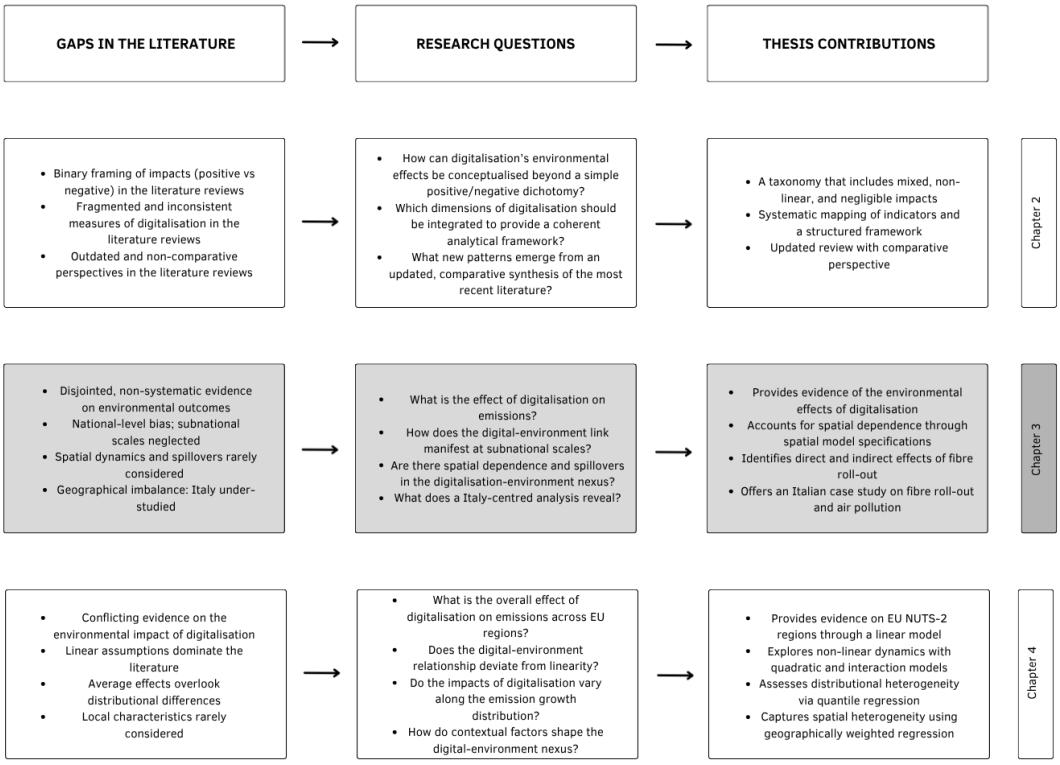
Chapter 3

Assessing the environmental impact of fibre optic adoption in Italian provinces

This study examines the environmental effects of digitalisation by analysing the relationship between fibre-optic broadband diffusion and air quality in Italian provinces from 2017 to 2020. The analysis focuses on the link between broadband deployment and variations in PM10 concentrations across NUTS-3 units. To assess this relationship, we use a panel data model with time fixed effects and a spatial econometric approach to capture interprovincial connections and identify both local and spillover effects. A mediation analysis further explores the role of fuel consumption in shaping the relationship between broadband and air quality. The results indicate that greater fibre deployment is associated with lower levels of air pollution, with effects extending to neighbouring provinces and demonstrating spatial spillovers. Reduced fuel consumption emerges as one of the mechanisms behind these improvements, possibly reflecting changes in mobility and commuting behaviour facilitated by digital connectivity.

Figure 3.1 highlights the part of the thesis framework corresponding to Chapter 3, which examines spatial dependence within the Italian context.

Figure 3.1: Position of Chapter 3 within the overall thesis framework.



3.1 Introduction

Air pollution poses a serious risk to public health, contributing to the incidence of strokes, heart diseases, lung cancer, and chronic and acute respiratory conditions and leading to millions of premature deaths globally (World Health Organization 2024). It also incurs substantial economic costs through premature mortality, migration and reduced working hours. It exacerbates spatial disparities in labour productivity, particularly in areas where extreme temperatures and environmental stresses are more pronounced (Zhang et al. 2024). Pollution may influence residential patterns, as households may relocate following health issues such as respiratory problems (Pan 2023). These effects underscore the necessity of effective pollution control policies to prevent significant human, social, and economic losses (Dechezleprêtre et al. 2019; Ding et al. 2024).

Digitalisation has the potential to influence air pollution both positively and negatively. Technologies like IoT sensors and real-time monitoring enhance energy efficiency and resource management, contributing to emission reduction (Wu et al. 2023). Digital solutions such as telecommuting and video conferencing diminish the necessity for commuting, alleviating urban congestion and enhancing air quality (Haseeb et al. 2019; Chien et al. 2021). Intelligent infrastructures, including traffic management systems and smart grids, also aid in alleviating road congestion and minimising energy losses (Shehzad et al. 2022). Targeted digital solutions, including digital place-based policies, can facilitate emission reductions by improving urban governance frameworks and strengthening local innovation capacities (Nie et al. 2025). Even the EU recognises the significance of digital technologies in mitigating pollution: the 2019 European Green Deal advocates for a green and digital transition as vital for decarbonisation and environmental enhancement (European Commission 2019).

Despite its benefits, digitalisation also brings environmental challenges. The production of electronic device has led to a significant increase in electronic waste and exacerbate natural resources extraction needed for their manufacture, resulting in the depletion of rare metals and environmental damage (Charfeddine and Kahia 2021; Awad 2022).The expansion of digital services trade often requires

substantial investments in energy-intensive infrastructure, especially during the initial phases of digitalisation, when production is constrained and carbon emission efficiency typically declines (Zhu and Hao 2019). The growth of data traffic and the expansion of digital infrastructure demand increasing amounts of energy. Data centres powered by non-renewable sources, risk exacerbating greenhouse gas emissions (GHG, Atsu et al. 2021).

Even within Europe, the impact of digitalisation is ambivalent: it could improve sustainability through more efficient production (Bianchini et al. 2023), but it could also increase energy consumption and e-waste (Ha et al. 2022). Countries with advanced levels of digitalisation typically decrease emissions, while those with lower levels may first see an increase before achieving long-term benefits (Kuzior et al. 2022). Acknowledging these complexities is pivotal, as the debate on digitalisation's environmental impacts remains open and multifaceted.

According to the literature, we identify four main gaps that we aim to address. First, little is known about how digitalisation affects the environment. Even though a lot of research has been done on the advantages and disadvantages of digitalisation, the evidence is still inconsistent and fragmented, which emphasises the need for a thorough examination. Second, a lot of research concentrates on the national level, frequently ignoring regional assessments and possibly overlooking important local variations that are crucial for assessing the effectiveness of policies in specific context (Díaz Dapena et al. 2021). There are two primary reasons why investigations at the regional level are essential. Digital policies are often designed, funded and implemented at the regional level, making regional analysis more relevant for guiding policy decisions (see European Committee of the Regions (2023)). On the other hand, every location has its own distinct environmental ecosystems and productive structures. It is therefore important to study environmental impacts at more precise spatial levels (Ghosh and Cartone 2020).

Third, the existing research does not examine spatial dynamics and spillover effects between regions. Since both air pollution and the impacts of digitalisation frequently extend beyond administrative boundaries, it is vital to account for these interconnections. Standard linear regression models assume that units, such

as regions or provinces, are identically and independently distributed. However, it is difficult to imagine that significant air quality degradation in one province would not negatively affect neighbouring provinces (Fang et al. 2015; Chen et al. 2017) From an economic and technological perspective, the high interconnection of our country's industrial systems suggests that spatial spillover phenomena can occur if a region experiences a strong increase in technological and digital capital. Acknowledging those effects can support digital growth through mechanisms of imitation, informal knowledge exchange, and labour flows. In such a context, therefore, spatial econometrics models seem preferable (Anselin 1988). Finally, there is a substantial lack of studies focused on Italy. Given Italy's territorial diversity and unique economic characteristics, an analysis at the local level could provide valuable insights into the relationship between digitalisation and air quality.

This study addresses these gaps taking into account a regional scale (NUTS-3, i.e., Italian provinces) to capture spatial spillovers overlooked in previous research. The aim is to investigate whether increased digital connectivity, measured by the diffusion of Fibre to the Home (FTTH), contributes to a reduction in air pollution or, conversely, exacerbates emissions. FTTH technology offers high-speed data transmission and greater reliability compared to other solutions, enabling the implementation of advanced applications such as telecommuting, telemedicine, and the Internet of Things (IoT). Our approach, based on broadband diffusion, assumes that increased network availability encourages greater use of digital services. The importance of FTTH is further highlighted by the Digital Italy 2026 strategy, which is part of the National Recovery and Resilience Plan (Presidenza del Consiglio dei Ministri 2021)[1].

Empirically, we employ a panel data model to examine the relationship between FTTH diffusion and air pollution, using longitudinal data in all 107 Italian provinces from 2017 to 2020. We then extend this analysis using a Spatial Autoregressive Model with Autoregressive Disturbances to capture the spatial dependence in both the dependent variable and the error terms. This approach allows for an examination of both direct impacts – which reflect changes within a

[1]This plan aims to ensure that all areas have access to high-speed and reliable internet connections, thus promoting economic growth and digital inclusion.

province – and indirect impacts, which capture how impacts spread to neighbouring provinces through spatial spillovers. To investigate the mechanisms underlying this relationship, we use a mediation analysis with fuel consumption as a proxy for vehicle mobility. This allows us to assess whether changes in air quality can be partially attributed to changes in transport-related emissions associated with improved digital connectivity. Our results show that FTTH deployment contributes to significant reductions in the concentration of air pollutants. Moreover, this occurs not only through direct improvements within provinces, but also through positive spillovers that amplify environmental benefits in neighbouring regions. Changes in emissions related to transport may partly explain these results.

The remainder of the paper is organised as follows. Section 3.2 presents an overview of the existing literature. Section 3.3 explains the methodology and data used in the analysis. Section 3.4 discusses the results obtained, and Section 3.5 is dedicated to the conclusions derived from the study.

3.2 Environmental implications of digital innovation

The environmental impact of digitalisation remains a controversial issue in the literature. Numerous studies underscore its potential to improve sustainability through emission reductions and increased energy efficiency; however, some also highlight its environmental costs, indicating a context-dependent and frequently non-linear relationship influenced by the degree of technological advancement and diffusion. On the positive side, digitalisation can contribute to the reduction of CO_2 emissions and the improvement of energy efficiency (Añón Higón et al. 2017; Danish 2019; Lange et al. 2020). Energy management systems based on IoT minimise energy waste in manufacturing (Ahmed et al. 2021), while advancement in Information and Communication Technologies (ICT) within services optimise business processes and resource management, reducing greenhouse gas emissions (GHG; Sun and Kim 2021). Transport technologies, including telecommuting and route optimisation reduce fuel consumption and emissions, improving air quality

(Haseeb et al. 2019; Chatti 2020; Baffour Gyau et al. 2023). Digitalisation promotes sustainable practices by encouraging resource reuse, recycling and reducing waste, and investments in green technologies (Wen et al. 2021; Ben Jebli et al. 2024).

The environmental costs associated with digitalisation must be acknowledged. The growth of digital infrastructures necessitates significant energy usage, primarily for the operation of computer systems and the powering of data centres, frequently sourced from non-renewable energy (Park et al. 2018; Arshad et al. 2020). The rise in data traffic and intensive internet usage in European Union countries has been associated with an increase in GHG emissions. The production and disposal of ICT equipment further intensify environmental challenges. The rate of technological obsolescence leads to an increase in electronic waste (Avom et al. 2020). The effects may also differ based on country's level of technological and economic development, with ICT adoption potentially raising emissions in developing countries through increased energy demand, while contributing to emissions reductions in developed countries through improved efficiency and renewable energy integration (Asongu et al. 2018; Ben Lahouel et al. 2024).

Digitalisation may produce environmental effects that extend beyond administrative boundaries. Spatial spillovers manifest through multiple channels, including the dissemination of green technologies, industrial advancement, and interregional knowledge exchange. Empirical evidence indicates that digital infrastructure and innovation have the potential to decrease emissions at local and adjacent levels, especially through technology transfer and collaborative efforts (Li and Wang 2022). The incorporation of digital tools in production and logistics within manufacturing can reduce emissions in interconnected urban regions (Sun and Kim 2021). In addition, the concentration of high-tech industries enhances knowledge spillovers and promotes the diffusion of environmental innovations across regions (Li et al. 2024). However, Li et al. (2025) demonstrate that digital technology innovation leads to increased emissions in neighbouring regions due to industrial relocation and investment flows, despite an overall net reduction effect.

While the literature on the environmental impact of digitalisation is extensive, few studies focus specifically on Italy. Given Italy's unique territorial and economic

diversity, a detailed examination at the provincial level can bring useful insights. Park et al. (2018) present mixed results, showing that ICT can have both positive and negative environmental impacts. However, focusing on Italy, their analysis shows that the impact of ICT is not statistically significant. Similarly, in a comparative study among countries such as China, Russia and Sweden, Chang et al. (2022) also find that ICT use in Italy does not lead to significant environmental improvements. These results highlight the need for a more detailed study of the role of advanced digital infrastructures such as FTTH in the Italian context.

Few studies have looked specifically at the environmental impact of broadband. However, fixed broadband – especially fibre – can reduce emissions through several processes. First, it enables energy-efficient production systems and intelligent management of logistics and resource use in manufacturing (Ahmed et al. 2021). Secondly, compared to mobile broadband, fixed broadband provides more stable and faster connections, which are essential for the efficient implementation of advanced digital technologies such as cloud computing, smart grids, and process automation, all of which contribute to reduced energy intensity (Quaglione et al. 2023). The environmental benefits are more pronounced in high-income or technologically advanced countries, where digital infrastructure is more effectively linked to clean technologies and energy-efficient practices (Khan et al. 2020; Awad 2022).

In summary, the literature provides valuable insights into the environmental impacts of digitalisation, but important questions remain about its role in promoting environmental sustainability. Regional perspectives are often ignored and the spatial dynamics of digitalisation, particularly in Italy, are rarely addressed. Furthermore, there is limited research on the environmental impact of broadband technologies such as fibre optics. To address these gaps, this study examines the relationship between digitalisation and the environment in Italy. Using a spatial econometric model, we investigate how the diffusion of FTTH at the provincial level affects air pollution, considering both direct effects and spillovers to neighbouring provinces.

3.3 Materials and methods

3.3.1 Econometric strategy

To analyse the impact of FTTH diffusion on air pollution levels in Italy, we adopt a methodological approach utilising panel data structure. To obtain a more detailed understanding of the effects, we conduct the analysis at the NUTS-3 level, thus considering provinces as the unit of observation. The panel model we use is as follows:

$$\boldsymbol{y}_t = \beta_0 \boldsymbol{i} + \boldsymbol{X}_t \boldsymbol{\beta} + \boldsymbol{\xi}_t + \boldsymbol{\varepsilon}_t \tag{3.1}$$

where for each period $t = 1, \ldots, T$, $\boldsymbol{y}_t$ is the $N \times 1$ vector of the dependent variable, $\boldsymbol{\beta}$ is the vector of P unknown parameters, β_0 is the intercept, $\boldsymbol{i}$ is an N-dimensional column vector containing all elements equal to 1, and $\boldsymbol{X}_t$ is the $N \times P$ matrix of explanatory variables. In (3.1), $\boldsymbol{\varepsilon}_t$ is the vector of independently and identically distributed (i.i.d.) errors with zero mean and variance σ_ε^2. To determine the choice between the fixed effects model and the random effects model, we use the Hausman test. TThe test results indicate that the model is better represented by a fixed-effects spatial structure. Hence, $\boldsymbol{\xi}_t$ represents the fixed effects that capture provincial time-invariant effect.

Spatial dependence is considered in the panel structure to account for cross-sectional dependence (Anselin 2010). In other words, spatial dependence reflects a situation where the values observed in one location or region depend on the values of observations in neighbouring locations (LeSage and Pace 2009). This spatial dependence implies that observations in nearby geographic areas can influence each other, and ignoring this dependence could lead to distorted results.

Traditionally, the most used models in spatial econometrics were the Spatial Autoregressive Model (SAR) and the Spatial Error Model (SEM). The SAR model focuses on endogenous interaction effects among dependent variables, while the SEM analyses interactions among error terms. With the evolution of spatial

modelling, models that combine various types of spatial interaction have been developed. Among these, the Spatial Autoregressive Model with Autoregressive Disturbances (SARAR), also known as the Spatial Autocorrelation Model (SAC), integrates both endogenous interaction effects among variables and correlations among error terms (Kelejian and Prucha 1998; Elhorst 2014).

In our study, we use a SARAR model as it provides a more comprehensive representation of spatial interactions, capturing both dependence among variables and correlations in the errors:

$$\boldsymbol{y}_t = \beta_0 \boldsymbol{i} + \boldsymbol{X}_t \boldsymbol{\beta} + \lambda \boldsymbol{W} \boldsymbol{y}_t + \boldsymbol{\xi}_t + \boldsymbol{u}_t \quad \text{with} \quad \boldsymbol{u}_t = \rho \boldsymbol{W} \boldsymbol{u}_t + \boldsymbol{\varepsilon}_t \tag{3.2}$$

where $\boldsymbol{W}$ is an exogenous spatial connectivity matrix of size $N \times N$. Specifically, $\boldsymbol{W}$ is a k-nearest neighbours matrix representing the distances between a province and its k nearest neighbours. We set $k = 5$, connecting each unit to its five nearest neighbours. Each element of $\boldsymbol{W}$, w_{ij}, is equal to 1 if province j is one of the five nearest neighbours of province i; otherwise, $w_{ij} = 0$. To facilitate integration into spatial models, we apply row standardisation to the $\boldsymbol{W}$ matrix. In this process, each value in the matrix is scaled so that the sum of the elements in each row equals 1, thus transforming the binary values into relative proportions that represent each province's connectivity fraction to its nearest neighbours.

The parameter λ represents the spatial autocorrelation of the dependent variable. It measures the intensity of the effect of dependent variables in neighbouring areas ($\boldsymbol{W}\boldsymbol{y}_t$) on the dependent variable in the unit under consideration ($\boldsymbol{y}_t$). A high value of λ suggests a strong influence of the values in surrounding areas on the dependent variable in the analysed province.

The parameter ρ indicates autocorrelation in the error term, capturing spatial dependence among errors by measuring how much the errors in one unit are correlated with errors in neighbouring units. A positive and significant ρ value implies that errors tend to be similar among neighbouring provinces, suggesting the presence of unobserved effects influencing the measurements.

When the value of ρ is not statistically different from zero, the model in (3.2) reduces to a SAR. Conversely, when $\lambda = 0$, the SARAR model simplifies to a Spatial Error Model, where only the parameter of spatial autocorrelation in the error is significant (Anselin 1988).

In this study, the analysis focuses on evaluating direct and indirect impacts rather than parameter estimates. Direct impacts measure the marginal effects directly attributable to a change in covariates within a single spatial unit. In other words, a direct impact reflects how a change in an explanatory variable in one location affects the dependent variable in the same location. Indirect impacts, on the other hand, measure the marginal effects resulting from changes in the independent variables of neighbouring units. These impacts represent how a change in a variable in one location can influence variables in the considered location through spatial relationships with surrounding areas. Indirect impacts can be interpreted as measures of spatial spillover effects. Total impacts are obtained by summing direct and indirect impacts. Direct and indirect impacts are calculated using the closed form of model (3.2) and by computing the matrix of partial derivatives of the dependent variable with respect to each explanatory variable. Specifically, the mean of the elements on the diagonal of the matrix of partial derivatives represents the direct impact of the variable, while the mean of the off-diagonal elements represents the indirect impact. To evaluate the variability of all impacts – direct, indirect, and total – and test the statistical significance of spillovers, we use a Monte Carlo routine.

To gain a deeper understanding of the mechanisms through which the diffusion of FTTH may influence pollution levels, we conduct a mediation analysis using fuel consumption as a proxy for vehicular transportation. Following Baron and Kenny (1986) framework, we first evaluate the direct effect of FTTH on pollution levels. We then examine whether FTTH influences fuel consumption, potentially reducing the need for physical commuting. Finally, we test whether fuel consumption mediates the relationship between FTTH and pollution by assessing whether its inclusion reduces the direct effect. A bootstrap test with extensive resampling is used to estimate the confidence intervals of the indirect effects, ensuring robustness. Time dummy variables are also included to control for temporal trends and unobserved

period-specific factors.

3.3.2 Data

The dependent variable in our study, *pollution*, is represented by PM10 levels. Fine particulate matter is a standard measure of air quality and is closely associated with numerous adverse health effects, including respiratory and cardiovascular diseases. The choice to use PM10 as the dependent variable is motivated by its relevance in the context of environmental policies and the availability of reliable data at the provincial level. Monitoring pollution levels allows for the precise evaluation of the impact of different independent variables on air pollution in Italian provinces.

The main independent variable considered in our study is the diffusion of FTTH technology (*connection*). The choice to focus on FTTH, rather than other forms of broadband connection, is motivated by the numerous advantages this technology offers. FTTH provides high-speed connection directly to users' homes, ensuring greater bandwidth and a more stable and reliable connection compared to copper connections or other hybrid technologies. These characteristics make FTTH particularly suitable for supporting advanced applications such as telecommuting, access to online services, and the IoT, which can reduce the need for physical travel and, consequently, emissions from vehicular traffic. Additionally, FTTH improves the energy efficiency of production processes and facilitates the implementation of real-time monitoring systems, allowing for more efficient management of energy resources. This can lead to a reduction in overall PM10 emissions. Therefore, the choice of FTTH reflects the desire to examine the impact of the most advanced network technologies and their contribution to environmental sustainability.

In developing our model, we selected control variables based on existing literature to ensure the reliability and validity of our findings. The industrial value added (*gva_ind*) is included in the model as an indicator of industrial economic activity. Industrial activities are often associated with higher PM10 emissions due to production processes involving the combustion of fossil materials, the use of heavy

machinery, and the generation of dust (Deabji et al. 2024). Industrial production can release particulates into the air through the use of boilers, furnaces, and other industrial equipment. Road freight transport by region of loading (*transport*) reflects the intensity of commercial traffic. This factor represents one of the main sources of PM10 emissions due to the combustion of fossil fuels in commercial vehicles (Demir et al. 2015; Domagała and Zych-Lewandowska 2021).

Population density (*density*) is included in the model as a measure of anthropogenic pressure on the environment. Provinces with higher population density tend to exhibit higher levels of air pollution due to the concentration of human activities that contribute to PM10 emissions, such as domestic fuel use (Ohlan 2015; Kostakis et al. 2023). The number of patent applications filed per province, represented as patents, is used as a proxy for innovation and research and development activities. A high number of patent applications can indicate increased innovative activity, which can have a dual effect on pollution. On the one hand, innovation can lead to cleaner technologies and more efficient production processes. On the other hand, it can be associated with increased industrial activity and, consequently, higher emissions (Chen and Lei 2018; Mensah et al. 2018).

In the set of control variables, we also included electricity consumption (Park et al. 2018). Specifically, energy consumption per worker is included as an indicator of energy intensity in different areas (*energy_intensity*). High electricity consumption per worker may indicate less sustainable practices, leading to higher levels of PM10 emissions. However, higher intensity could also reflect the adoption of advanced technologies that, while requiring more electricity, reduce overall PM10 emissions through more efficient processes. Investments (*investments*), represented by Gross Fixed Capital Formation (GFCF) (Meng et al. 2022), reflect the provinces' commitment to new infrastructure and technologies. High levels of investment can improve long-term production efficiency but may also lead to a temporary increase in emissions during construction and development phases.

The analyses were conducted on a panel dataset that combines data related to all Italian NUTS-3 units, totalling 107 provinces, observed over the period 2017-2020. The data used to define the variables were collected from various sources. For

the variable *pollution*, representing PM10 levels ($\mu g/m^3$), the data comes from the European Environment Agency (EEA)[2]. The variable *connection* is defined as the ratio of the number of households reached by FTTH technology to the population on 1st January. Data on the number of households reached by FTTH are provided by the Italian Communications Authority (AGCOM)[3] and are also used to calculate the DESI indicator The population on 1st January is taken from the Annual Regional Database of the European Commission (ARDECO)[4].

The variable *gva_ind* is calculated as the ratio of the Gross Value Added (GVA) at constant prices of the industry[5] to the total GVA at constant prices, expressed in millions of euros of 2015. Data for this variable come from ARDECO. *investments* are defined as the ratio of Gross Fixed Capital Formation (GFCF) to Gross Domestic Product (GDP), both expressed in millions of euros at 2015 prices. Data for these variables are also provided by ARDECO. The variable *transport* is defined as road freight transport by region of loading, measured in total goods transported. This value is normalized by the number of employees, expressed in persons. Data related to freight transport and employees come from Eurostat[6]. The indicator *density* is calculated as the population on 1st January divided by the area in square kilometers of the provinces (data from Eurostat). The variable *patents* variable is represented by the number of patent applications filed divided by the population on 1st January. Data on patents applications is provided by the Ministry of Enterprise and Made in Italy[7]. Lastly, *energy_intensity* is calculated

[2]European Environment Agency (EEA). Air Quality Health Risk Assessments. Available at https://www.eea.europa.eu/en/datahub/datahubitem-view/49930245-dc33-4c47-93b8-9512f0622ebc

[3]Italian Communications Authority (AGCOM). Dashboard for the Study of Connectivity Indicators (DESI). Available at https://agcom.maps.arcgis.com/apps/dashboards/770a9ca1c3684acc9bff5df3f2150854

[4]European Commission, Joint Research Centre (JRC). Annual Regional Database of the European Commission (ARDECO). Available at https://urban.jrc.ec.europa.eu/ardeco/explorer?lng=en

[5]In this study, the term "industry" refers to the sectors defined under categories B to E in the ARDECO database, which include Mining and quarrying (B), Manufacturing (C), Electricity, gas, steam and air conditioning supply (D), and Water supply; sewerage, waste management and remediation activities (E). The construction sector is excluded from this definition.

[6]Eurostat. Regional Database. Available at https://ec.europa.eu/eurostat/web/regions/database

[7]Italian Patent and Trademark Office (UIBM), under the Ministry of Enterprise and Made in Italy. Patent Statistics. Available at https://statistiche.uibm.gov.it

as electricity consumption, measured in TWh, divided by the number of employees. Data on electricity consumption are sourced from Terna[8], the Italian national transmission system operator. All variables are used in logs in the models.

For the mediation analysis, the variable *fuel* was constructed by summing the consumption of gasoline, diesel, and liquefied petroleum gas (in tons) from the Petroleum Bulletin of the Italian Ministry of Environment and Energy Security and dividing it by provincial employment levels. This measure, representing fuel consumption per worker, serves as a proxy for work-related vehicular transportation. Given the potential impact of FTTH diffusion and remote working on commuting patterns, this variable is used to explore transportation's mediating role between digitalisation and pollution.

3.4 Empirical results

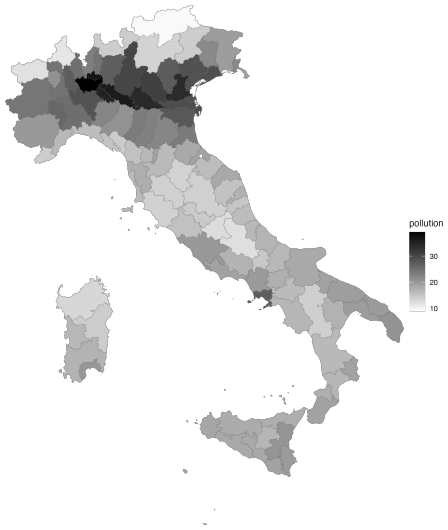
To provide an overview of the dataset, Table 3.1 presents the descriptive statistics of the variables used in the analysis. The PM10 levels recorded in Italian provinces for the years 2017 and 2020 are shown in Figure 3.2, respectively. For the same years, Figure 3.3 illustrates the level of FTTH, highlighting the growth in coverage across Italy over the considered period.

Table 3.1: Summary statistics.

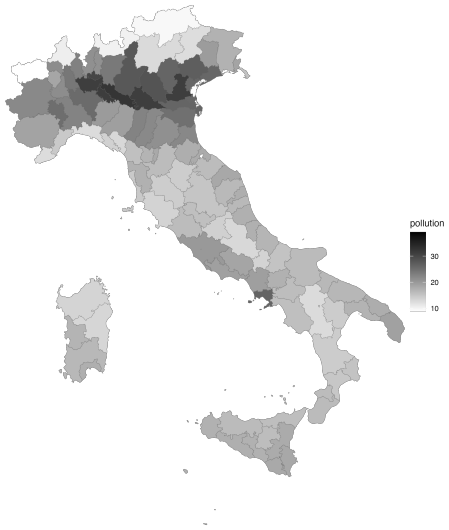
Variable	Obs.	Mean	SD	Min	Max
pollution	428	19.068	5.135	8.610	39.200
connection	428	0.067	0.078	0.000	0.470
gva_ind	428	0.194	0.083	0.048	0.405
transport	428	0.040	0.026	0.006	0.162
density	428	265.538	377.057	35.459	2587.426
patents	428	0.003	0.015	0.000	0.151
energy_intensity	428	0.020	0.026	0.001	0.154
investments	428	0.177	0.020	0.137	0.246

[8]Terna. Statistical Publications. Available at https://www.terna.it/it/sistema-elettrico/statistiche/pubblicazioni-statistiche

Figure 3.2: Quantile maps of the variable *pollution* across Italian provinces.

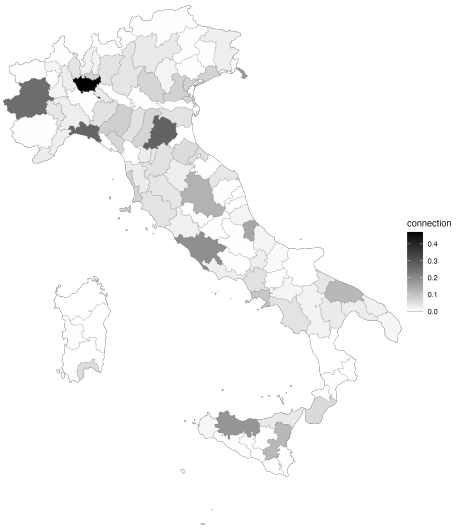


(a) *pollution* quantile map (2017).

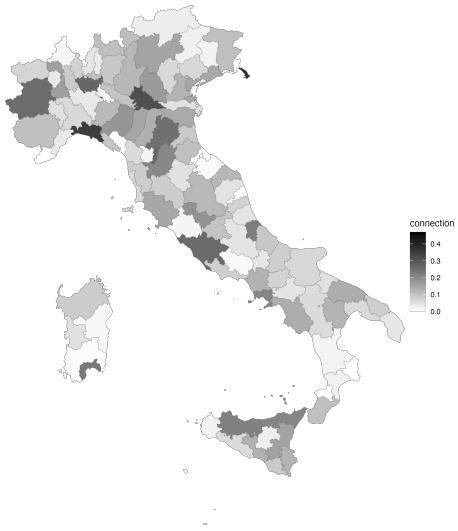


(b) *pollution* quantile map (2020).

Figure 3.3: Quantile map of the variable *connection* across Italian provinces.



(a) *connection* quantile map (2017).



(b) *connection* quantile map (2020).

The analysis covers a period in which several events occurred, in particular the COVID-19 crisis in 2020. We estimate fixed effects with time dummies using

the maximum likelihood method. Our results (Table 3.2) show that FTTH diffusion significantly contributes to the reduction of PM10 concentrations in Italian provinces. Specifically, the estimated coefficient associated with this variable is -0.634, statistically significant at the 1% level, suggesting that a 1% increase in FTTH coverage is associated with a 0.634% reduction in PM10 levels. This finding suggests how the spread of FTTH contributes to reducing air pollution. This can happen through several possible mechanisms: it facilitates remote access to advanced digital services, reduces the need for physical travel for work and other daily activities. Additionally, FTTH allows for efficient energy usage by enabling smart technologies that optimise energy consumption. FTTH also requires fewer resources for operation and maintenance, compared to traditional technologies. Finally, FTTH facilitates the integration of real-time monitoring systems and IoT technologies, which contribute to sustainable resource management. As discussed previously, these developments could reduce emissions associated with inefficiencies in production processes.

Industry and road transport intensity are identified as factors contributing to the increase in PM10 levels, alongside other controls. The estimated coefficient for industrial value added, significant at the 5% level, indicates that a 1% increase in industrial activity results in a 0.062% increase in PM10 levels. This finding is consistent with prior research indicating that industrial activity impacts air quality and elevates emissions from fossil fuel combustion (Zhu et al. 2019). Likewise, a 1% increase in road transport is associated with a 0.075% rise in PM10 levels, underscoring vehicular emissions (Essen et al. 2011). The population density exhibits a coefficient of 0.198, significant at the 1% level, suggesting that provinces with higher population density encounter increased pollution as a result of human activities, including commuting and domestic heating. Densely populated areas generally exhibit inferior air quality as a result of limited ventilation, decreased pollutant dispersion, and ongoing pollutant accumulation in the atmosphere (Borck and Schrauth 2021).

Technological innovation (*patents*) exhibits a positive effect on PM10 levels (0.015, significant at the 10% level), suggesting that innovation may stimulate economic activity, leading to a temporary increase in emissions. In the long term, it may

promote the advancement of cleaner technologies, leading to a reduction in pollution overall. The long-term effects of innovation may not be entirely reflected within the study period. The impact of innovation on pollution is likely more nuanced, with potential benefits that may only become apparent over time. Indeed, Li et al. (2021) observe an inverted U-shaped relationship, suggesting that while innovation may initially increase emissions due to the rebound effect, it can eventually lead to environmental improvements through the adoption of greener technologies. The coefficient for energy consumption per worker is negative and significant at the 5% level. This indicates that although higher energy consumption per worker may reflect less sustainable practices, in some cases, it can indicate the adoption of advanced technologies that, despite the increased energy use, ultimately reduce PM10 emissions through more efficient processes (He et al. 2022). The coefficient for the investments is not significant.

This study contributes by addressing externalities and spillover effects. Therefore, we extend the analysis by employing spatial specifications for our panel model, *i.e.*, the SAR, SEM, and the SARAR model with fixed effects. The models are all estimated by maximum likelihood and the results are presented in Table 3.2. As the SARAR (Table 3.2, column (d)) model is the most representative (see R-squared), we focus mainly on the results from this model in the comments.

The FTTH connection maintains a negative coefficient of -0.586, significant at the 1% level. This suggests that the impact of digitalisation on reducing PM10 is significantly enhanced when spatial dynamics are considered. Unlike in the FE model, the coefficient for industrial value added is not significant in this case. Road transport intensity and population density continue to show a significant impact on PM10, exhibiting higher coefficients than those observed in the fixed effects model. Technological innovation continues to exert a beneficial impact on PM10 within this model. Energy consumption per worker also becomes more relevant in the spatial model, with a negative coefficient of -0.057, significant at the 1% level. This result supports the idea that higher energy consumption per worker, associated with the adoption of advanced technologies, can contribute even more significantly to reducing emissions when spatial effects are considered. Investments maintain a non-significant coefficient.

The spatial parameter estimates of the SARAR model, λ and ρ, are both significant at the 1% level, highlighting the importance of spatial dependence. The λ, with a value of 0.436, indicates a strong positive autocorrelation in PM10 levels across neighbouring provinces, suggesting that pollution in one province tends to increase pollution levels in nearby provinces. The parameter ρ represents the autocorrelation of the error term, indicating a negative spatial dependence among unobserved variables. This implies that the residuals between proximate points tend to differ significantly. The significance of both λ and ρ confirms the importance of considering spatial dynamics when understanding the impact of various variables on air pollution, as interactions between neighbouring provinces can either amplify or mitigate local effects.

Table 3.2: Coefficients estimated from the panel linear model with time fixed effects, the SAR, the SEM, and the SARAR model with time fixed effects.

	FE	**SAR–FE**	**SEM–FE**	**SARAR–FE**
	(a)	(b)	(c)	(d)
log(connection)	-0.634***	-0.496***	-0.515***	-0.586***
	(0.177)	(0.186)	(0.174)	(0.147)
log(gva_ind)	0.062**	0.063*	0.051*	0.027
	(0.029)	(0.029)	(0.028)	(0.024)
log(transport)	0.075***	0.076***	0.085***	0.082***
	(0.017)	(0.017)	(0.017)	(0.014)
log(density)	0.198***	0.190***	0.199***	0.194***
	(0.015)	(0.015)	(0.014)	(0.013)
log(patents)	0.015**	0.015**	0.029***	0.029***
	(0.007)	(0.007)	(0.007)	(0.006)
log(energy_intensity)	-0.025**	-0.024**	-0.048***	-0.057***
	(0.011)	(0.011)	(0.011)	(0.009)
log(investments)	-0.055	-0.056	-0.085	-0.082
	(0.118)	(0.118)	(0.110)	(0.094)
Spatial autoregressive coefficient (λ)	–	-0.126	–	0.436***
		(0.087)		(0.062)
Spatial error parameter (ρ)	–	–	-0.646***	-0.750***
			(0.136)	(0.136)
R^2	0.41	0.42	0.41	0.46

Standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The SARAR model enables the calculation of direct, indirect, and total impacts, offering a comprehensive overview of the effect of digitalisation on air quality. Table 3.3 presents these findings.

The diffusion of FTTH significantly influences the reduction of PM10 levels, with notable effects both locally and on neighbouring provinces. The coefficient of the direct impact of the *connection* variable is -0.599, and it is highly significant at the 1% level. This indicates that a 1% increase in FTTH diffusion within a province leads to a 0.6% reduction in PM10 levels in that same province. This result not only confirms the effectiveness of fibre optics in reducing pollutant emissions but also suggests a potential role for FTTH in promoting the modernisation of local infrastructures. The diffusion of FTTH not only supports the reduction of emissions from transportation but can also facilitate the integration of smart technologies, improving energy efficiency and environmental resource management. Thus, this direct impact could contribute to a gradual transformation of the local economy toward greener models.

Indirect impact is considerable, with a coefficient of -0.442. This shows that increasing FTTH diffusion in one province lowers PM10levels in that province and in surrounding provinces. The spillover effects resulting from the diffusion of FTTH technology may manifest through various mechanisms. Advanced digital technologies in one province might inspire similar practices in other provinces, especially if they share infrastructure or economic networks. Digital connectivity can increase interprovincial collaboration, reducing physical transportation and PM10 emissions in surrounding provinces. FTTH can improve energy efficiency in neighbouring provinces by sharing superior knowledge and technologies. Companies in high-FTTH locations may indirectly affect operating practices in surrounding provinces, encouraging the adoption of green technologies (Liu et al. 2022). Incentives for FTTH dissemination can also establish provincial synergies, reducing emissions. Provinces with higher FTTH penetration can inspire comparable legislation and raise awareness of environmental sustainability (Du et al. 2023). Imitation and technology diffusion promote territorial cohesion and accelerate national sustainability (Boschma et al. 2013; Capello and Lenzi 2021).

The sum of the direct and indirect impacts results in a total impact of -1.042, which is highly significant. This finding suggests that the expansion of the FTTH network has a broadly positive effect on air quality, substantially reducing PM10 levels on a wider geographical scale. These results confirm that the diffusion of FTTH technology is a key component in the strategy for reducing air pollution. The ability of fibre optics to support remote work, optimise energy resource usage, and reduce reliance on traditional transportation translates into a significant improvement in air quality, not just at the local level.

The road freight transport has a significant impact on PM10 levels in the Italian provinces, with a direct impact of 0.087 and an indirect impact of 0.063 on adjacent areas. Population density has a similar effect on air, with a direct effect of 0.199 and an indirect effect of 0.146. This highlights the importance of local emissions and the dispersion of pollutants to neighbouring areas (Sun et al. 2023). The complexity of innovative activity is shown by patent metrics. Technological progress, while generally beneficial, is associated with increased PM10 levels, with a direct impact of 0.03 and an indirect impact of 0.022, both significant at the 1% level. This suggests that industrial and commercial links encourage production and emissions beyond the province of origin. In contrast, energy intensity, defined as electricity consumption per employee, has a negative impact on PM10, with a direct coefficient of -0.058 and an indirect coefficient of -0.042. This shows that a decrease in pollution, both locally and in nearby locations, is linked to increased energy efficiency.

Table 3.3: Direct, indirect and total impacts from the SARAR fixed effect model.

	Direct (a)	**Indirect** (b)	**Total** (c)
log(connection)	-0.599***	-0.442***	-1.042***
	(0.156)	(0.168)	(0.305)
log(gva_ind)	0.026	0.018	0.045
	(0.024)	(0.018)	(0.041)
log(transport)	0.087***	0.063***	0.150***
	(0.014)	(0.018)	(0.027)
log(density)	0.199***	0.146***	0.345***
	(0.013)	(0.035)	(0.039)
log(patents)	0.030***	0.022***	0.052***
	(0.005)	(0.006)	(0.009)
log(energy_intensity)	-0.058***	-0.042***	-0.101***
	(0.009)	(0.012)	(0.019)
log(investments)	-0.085	-0.061	-0.146
	(0.092)	(0.069)	(0.159)

Standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The mediation analysis results (Table 3.4) reveal how FTTH diffusion influences pollution levels in Italian provinces. The Average Causal Mediation Effect, representing the effect mediated through fuel consumption, is -0.169, indicating that reduced fuel consumption significantly contributes to pollution reduction. The Average Direct Effect of FTTH diffusion, without considering the mediator, is -0.332, suggesting a modest direct effect significant at the 10% level. The total effect, combining both mediated and direct effects, is -0.501, confirming a substantial overall reduction in pollution. Notably, approximately 33.4% of the total effect is mediated by reduced fuel consumption, highlighting transport emissions as a key mechanism linking FTTH deployment to improvements in air quality. The results suggest that digital technologies like FTTH reduce the need for physical commuting, lowering emissions and improving air quality. However, as fuel consumption explains only one-third of the total effect, other mechanisms – such as enhanced energy efficiency, reduced energy waste, or optimised industrial processes – likely contribute to the overall impact of FTTH on air quality.

Table 3.4: Mediation analysis results of FTTH's impact on pollution through fuel consumption.

	Estimate	**Lower 95% CI**	**Upper 95% CI**	**p-value**
Average Causal Mediation Effect	-0.169	-0.286	-0.070	<2e-16***
Average Direct Effect	-0.332	-0.712	0.040	0.078*
Total Effect	-0.501	-0.878	-0.130	0.009***
Proportion Mediated	0.334	0.126	1.160	0.009***

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

3.5 Conclusions

The aim of this study was to assess the impact of FTTH technology deployment on air pollution levels in Italian provinces between 2017 and 2020, addressing existing gaps in the literature. The findings indicate that the expansion of FTTH infrastructure significantly reduced PM10 concentrations across Italian NUTS-3 regions, with measurable spillover effects on neighbouring provinces. A preliminary analysis confirmed that the spread of FTTH is associated with a consistent improvement in air quality, reinforcing the notion that digital connectivity can contribute not only to economic development but also to environmental sustainability.

The spatial impact assessment further revealed that the environmental benefits of FTTH extend beyond the provinces where it is deployed. Direct effects show substantial reductions in PM10 levels locally, while indirect effects – interpreted as spatial spillovers – suggest that adjacent provinces benefit through shared knowledge, increased interaction, and shifts in mobility patterns. These results highlight the importance of accounting for spatial interdependencies when evaluating the environmental implications of digital infrastructure. Accordingly, policy strategies should place greater emphasis on coordinated digital investment across territories, considering the functional links between regions and the potential for wider territorial benefits.

The analysis also confirms that road freight intensity and population density exert a significant positive influence on PM10 concentrations, especially when

spatial dynamics are incorporated. Conversely, energy intensity exhibits a negative association with pollution, suggesting that higher energy use per worker may reflect the adoption of advanced, energy-efficient technologies. Innovation, proxied by patent activity, is associated with increased emissions in the short term, likely due to intensified production activity. However, over time, innovation may foster the uptake of cleaner technologies and more sustainable practices.

Mediation analysis demonstrates that the environmental benefits of FTTH deployment are partially explained by a reduction in commuting-related emissions. Using fuel consumption as a proxy for mobility, the analysis indicates that improved digital infrastructure can lower reliance on private vehicles, likely by facilitating remote work and reducing the need for daily commuting. Approximately one-third of the observed reduction in PM10 levels is mediated through this channel, highlighting the relevance of behavioural changes in shaping the environmental outcomes of digitalisation.

In conclusion, this study provides robust evidence that FTTH deployment contributes to improved air quality, both locally and across neighbouring territories. These effects are partly driven by a decline in fuel consumption linked to reduced commuting, reinforcing the role of digital infrastructure in transforming mobility patterns. Overall, the findings underscore the broader significance of digital connectivity in shaping environmental dynamics at both the local and regional levels, with important implications for the design of spatially-aware digital and environmental policies.

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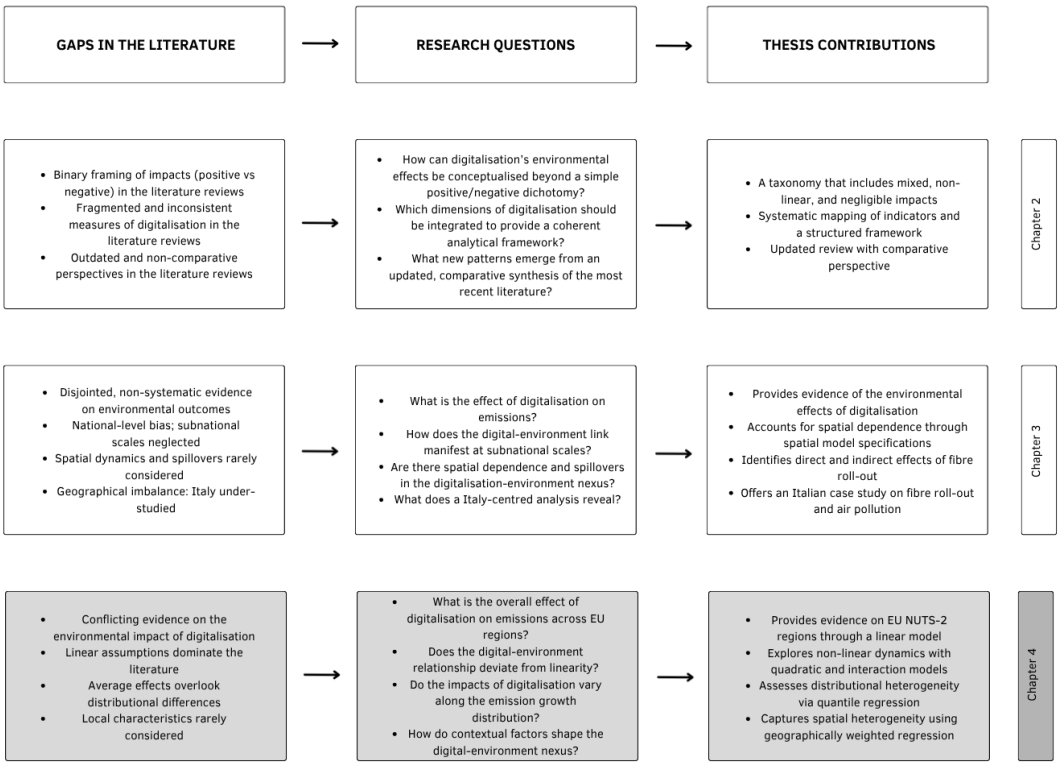
Chapter 4

Does regional heterogeneity matter for the relationship between digitalisation and the environment?

This chapter examines whether digitalisation exerts uniform environmental effects across European regions. Using NUTS-2 data, digitalisation is represented by two complementary dimensions: internet access, reflecting household connectivity and digital inclusion, and connection quality, which relates more closely to business functions and productive efficiency. Per-capita carbon emissions growth captures environmental change. Missing data are estimated using Bayesian interpolation, and Quantile Regression and Geographically Weighted Regression are employed to address distributional and spatial heterogeneity. The results reveal two main patterns. Across the emissions distribution, digitalisation proves most beneficial in regions undergoing transition, where efficiency gains can materialise, while its impact weakens at both extremes. Spatially, local features condition these effects: enhanced connectivity supports emission reductions in less connected areas but may intensify energy demand in advanced or carbon-intensive regions. Overall, the findings show that the environmental footprint of digitalisation depends critically on regional contexts and development paths.

Figure 4.1 situates Chapter 4 within the overall thesis framework, emphasising its focus on regional heterogeneity in the environmental effects of digitalisation across European Union.

Figure 4.1: Position of Chapter 4 within the overall thesis framework.



4.1 Introduction

Digitalisation has changed how economies and societies operate, reshaping the dynamics of production, distribution, and consumption (Butollo 2021; Helbing and Hausladen 2022). Digitalisation represents an opportunity for re-addressing the human-natural environment relationship to achieve more sustainable regional futures. The term refers not only to the widespread adoption of digital technologies but also to the broader changes these technologies bring to social and economic structures (Lagarde 2020). This process spans from businesses to individuals and households, which are increasingly embedded in a digital ecosystem characterised by connected devices, online platforms, and an ever-growing flow of data.

The broad availability of the internet and the increasing accessibility of digital devices has brought both benefits and challenges. It has increased productivity, improved access to information, simplified administrative processes, and fostered innovation across sectors (Cambini et al. 2023). This is true not only from a technological perspective, but also in economic and social terms. In fact, the digital revolution acts as a powerful catalyst for economic growth by increasing productivity through process automation and greater efficiency in value chains (Evangelista et al. 2014). However, digitalisation has raised critical issues regarding unequal access to technology. While holding potential to drive sustainable development, there remains a significant disparity among regions and social groups in terms of access to advanced digital infrastructure, high-speed connection, and technological devices (Gomes and Dias 2025). These inequalities risk widening economic divides and benefiting only the most advantaged regions (Capello and Caragliu 2024).

New methods of increasing energy efficiency and reducing emissions have been made possible by the development of digital technologies. Real-time digital monitoring and automated systems in industry maximise output while reducing waste and resource consumption (Taneja and Mandys 2022). The increase in internet access has been linked to a decrease in pollution levels (Ozcan and Apergis 2018). Changes in daily routines enabled by digitalisation, such as remote work, online services, and e-commerce, can also help reduce emissions associated with

traditional infrastructures. However, expected energy savings are often offset by increased digital consumption due to the so-called rebound effect (Zhu and Lan 2023). This highlights that digitalisation is not an environmentally neutral process but a transformative force whose net effect remains deeply contested. Indeed, its impact on energy consumption, emissions, and resource use is increasingly significant. The expansion of data-driven industries has increased demand for electricity, as cloud computing, artificial intelligence, and next-generation networks require constant high-power processing (Peng et al. 2023). Rapid technological advances accelerate resource depletion and electronic waste, especially where recycling infrastructure struggles (Cheng et al. 2019). Together, these dynamics confirm that digitalisation has become a decisive driver of environmental change, making its study essential for understanding pathways to sustainability.

Countries and international institutions – such as the European Union (EU) – placed sustainability at the heart of their digital strategy. Initiatives such as the European Declaration on Digital Rights and Principles – which explicitly includes sustainability as one of its key principles – have reaffirmed its commitment to a digital transformation that prioritises environmental responsibility, cohesion, and security in the EU[1]. Therefore, the European Union is committed to a cohesive approach while putting economic and financial resources at stake for European territories[2]. Indeed, ambitious strategies at the continental scale confront uneven local realities, where the environmental consequences of digitalisation are shaped less by shared objectives than by regional disparities. Despite this, significant disparities between locations persist beside geographical patterns of disadvantaged regions.

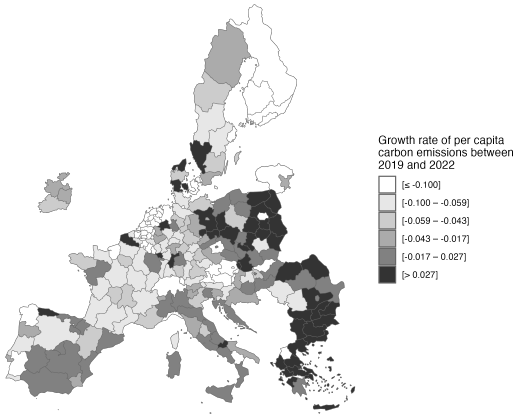
These differences can be found by looking at the territorial variations in Figure 4.2. Figure 4.2a shows the spatial distribution of per capita emissions growth; Figure 4.2b the percentage of households with internet access; and Figure 4.2c summarises the average upload speed across European NUTS-2 regions. Taken

[1]European Commission. (2025). *European Declaration on Digital Rights and Principles*. Retrieved from https://digital-strategy.ec.europa.eu/en/node/10650/printable/pdf

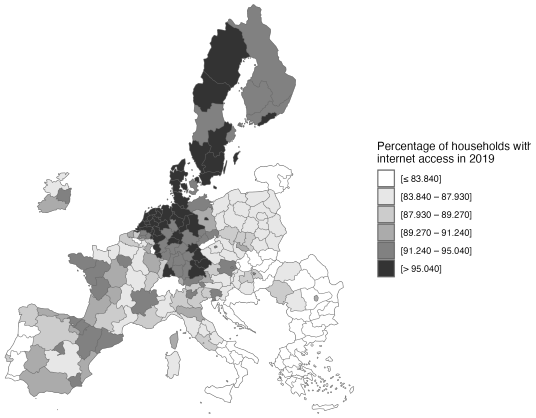
[2]European Union. (2021). *Regulation (EU) 2021/1058 on the European Regional Development Fund and on the Cohesion Fund*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R1058

together, these patterns indicate that proximity and geographical characteristics influence the relationship between digitalisation and environmental sustainability. The environmental effects of digital technologies are dependent upon the regional context: areas with strong capacities and technological pathways aligned with green innovation are more successful at converting digitalisation into efficiency gains, while less advantaged regions may face increasing emissions (Bianchini et al. 2023). These outcomes are also shaped by factors such as the production system or patterns of energy demand. Moreover, regions are embedded in wider networks through which changes in one area reverberate in others (Fan et al. 2025). This perspective situates the study within regional environmental economics, aiming to investigate how local factors influence the digital-environment relationship in the European Union.

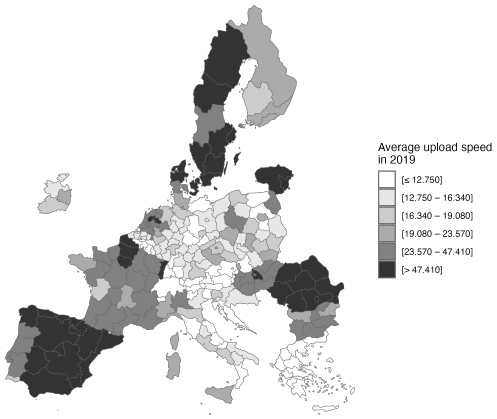
Figure 4.2: Quantile maps illustrating regional patterns across European NUTS-2 regions.



(a) Growth rate of per capita CO_2 emissions (2019-2022).



(b) Households with internet access (2019).



(c) Average upload speed (2019).

Understanding how digitalisation affects the environment is therefore essential. Its impacts appear to be neither linear nor uniform, but shaped by local capacities, production systems and interdependencies across regions. Without a clearer grasp of these dynamics, policies risk overlooking the ways in which digital technologies can both accelerate and undermine the green transition.

We identify four gaps in the academic debate on the link between digitalisation and sustainability at territorial level. First, while some studies suggest that

ICT improves energy efficiency and reduces emissions (Lu 2018; Agarwala et al. 2021; Chien et al. 2021), others highlight the growing demand for electricity and increased emissions associated with the proliferation of digital infrastructure and services (Gensch et al. 2017; Park et al. 2018). These conflicting results mean that the impact of digitalisation is not always clear. Second, the assumption of a linear relationship between digitalisation and environmental outcomes is unrealistic. The impact of digital technologies is expected to change: it may vary in sign and magnitude based on the level of digital development, presenting potential advantages in initial stages and risks of increased emissions as digital maturity progresses, or conversely (Ahmadova et al. 2022; Lei et al. 2023). Third, most analyses focus on average effects and rarely examine how the implications of digitalisation vary across different environmental conditions. This overlooks the possibility that impacts vary along the distribution of emission outcomes, with some regions more exposed to benefits or costs than others. Lastly, little attention has been given to local features. Regional innovation capacity and industry architecture, for example, may influence whether digitalisation improves efficiency or confines economies to carbon-intensive trajectories (Wang et al. 2022; Zhang and Du 2025).

To address these four gaps, we begin with a global Ordinary Least Squares (OLS) approach to establish the average link between digitalisation and emissions. To go beyond averages, we use Quantile Regression (QR), which illustrates the varying impacts throughout the emissions distribution and underscores the different experiences of places facing low, moderate, or high environmental pressures. We then employ Geographically Weighted Regression (GWR, Fotheringham et al. 2002), which uncovers how local features influence the relationship between digitalisation and the environment. Across these approaches, we also include quadratic and interaction terms, enabling us to identify potential non-linearities and determine whether the environmental impacts of digitalisation vary at different stages of development.

The findings indicate three different patterns. First, different aspects of digitalisation have distinct consequences: access to the internet predominantly alleviates issues in less connected regions, whilst connection quality yields more extensive

results, exhibiting diminishing returns at elevated speeds. Second, the consequences of digitalisation are unevenly distributed: quantile regressions indicate that advantages are more pronounced in areas with moderate emissions growth. Third, spatial variability is evident: local characteristics determine whether digitalisation facilitates decarbonisation or perpetuates carbon-intensive pathways. These findings contribute to the current literature by demonstrating that digitalisation is not a consistent catalyst for environmental change. By including non-linear, distributional, and spatial perspectives, we offer a more detailed comprehension of the interaction between digital technologies and regional environments. This deeper consideration of heterogeneity extends previous work and offers new insights for policies that seek to align the digital and green transitions.

In the paper we contribute by discussing several methodological approaches to offer a detailed study on the impact of digitalisation and fill the gaps present in the current literature. Particularly, a deeper consideration of spatial heterogeneity can drive new policy insight. Results suggest that spatial heterogeneity is not a matter of between-country disparities, as many within-country differences are evident. Accordingly, we identified three principal findings. Primarily, different aspects of digitalisation have different impacts on emissions, with internet quality demonstrating more consistent relationships. Secondly, the environmental impact of digitalisation significantly differs in terms of emissions distribution: some regions gain from improved digitalisation, whereas others may face ecological drawbacks. Third, spatial variability is evident: regional characteristics influence the direction and intensity of the digital-environmental connection.

The remainder of the paper follows. Section 4.2 provides an overview of the existing literature. Section 4.3 explains the data and methodology used in the analysis. Section 4.4 discusses the results obtained, and Section4.5 is dedicated to the conclusions and policy implications derived from the study.

4.2 Digitalisation and the environment: an overview of the literature

Research has increasingly shifted focus from the mere use of digital technologies to their broader contributions, both positive and negative, to natural ecosystems. The growing adoption of technologies by individuals and households – such as smartphones, computers, smart home devices, and high-speed internet connections – has several implications for environmental sustainability (Chatti 2020). However, the debate remains open.

Digitalisation offers several pathways for lowering CO_2 emissions, from reshaping mobility patterns and transforming access to services to enabling smarter energy use at home. Remote working, for example, reduces the need for daily commutes, easing pressure on both private and public transport systems and directly cutting transport-related emissions. Digital platforms, including e-commerce, e-government, and e-learning, also diminish the need for physical transportation in daily activities, potentially leading to significant decreases in overall travel demand (Ahmed et al. 2021; Briglauer et al. 2023). The diffusion of smart home devices additionally enhances the management of household energy consumption. Integrating devices with intelligent energy networks enables homes to monitor consumption in real time, shift demand from peak hours, and improve overall electricity efficiency. This not only facilitates cost reduction but also mitigates pressure on power grids, underscoring the capacity of digitalisation to diminish CO_2 emissions (Balta-Ozkan et al. 2013; Liang 2024).

However, digitalisation also brings about a series of environmental side effects, largely related to increasing energy consumption. The rising use of electronic devices by households has led to a higher demand for electricity (Sadorsky 2012), particularly for powering and charging these devices (Røpke et al. 2010). The infrastructure necessary to support growing connectivity requires vast amounts of energy. Data centres are among the largest sources of energy consumption in global digitalisation, as they are responsible for operating cloud computing platforms and managing real-time data flows (Rong et al. 2016). Although some

companies are adopting initiatives to reduce their energy footprint by utilising renewable sources, a significant portion of this energy still comes from fossil fuels, thereby increasing emissions. In addition, the production and disposal of electronic devices pose a significant environmental threat. The manufacturing of devices such as smartphones, computers, and tablets requires natural resources, including rare metals and other critical materials, which are extracted through highly polluting processes. Moreover, the production of these devices involves substantial greenhouse gas emissions and generates industrial waste that is difficult to manage. The lifespan of digital devices is often short, and the growing demand for new technologies leads to an exponential increase in electronic waste (Heeks et al. 2015). The disposal of this waste can result in the release of toxic substances into the environment, such as mercury and lead, with severe consequences for ecosystems and human health (Rautela et al. 2021).

Digitalisation does not have a uniform impact on the environment. Economic systems, energy infrastructures and regulatory frameworks, for instance, all influence how its impacts manifest themselves in complex and regionally specific ways. In some contexts, it promotes energy efficiency and reduces emissions, while in others it increases energy consumption and carbon footprints. The expansion of ICTs has been associated with higher emissions in areas with relatively low levels of pollution, as growing digital demand may exceed possible efficiency gains (Lee et al. 2023). On the other hand, by improving resource management and regulatory oversight, digital technology can help reduce emissions in regions with significant environmental degradation (Albaity and Awad 2023). Similarly, in high-income countries with more developed digital infrastructure, ICTs increase carbon productivity, promoting economic growth with less environmental impact (Yu and Liu 2024). However, the growth of digitalisation tends to exacerbate rather than lessen environmental stressors in less-developed countries, where electricity grids frequently rely on fossil fuels (Khan et al. 2020).

As industrial upgrading and better environmental governance require active policy intervention, their ability to drive green transformation in less developed regions depends on regulatory support (Wang et al. 2022). Targeted sustainability policies, such as carbon trading schemes and sector-specific incentives, are crucial for trans-

lating digital breakthroughs into real emission reductions in highly industrialised areas, where digital growth alone is insufficient to limit emissions. These outcomes are further shaped by the urban dimension: higher-density areas tend to benefit more from the decarbonisation effects of digitalisation due to improved infrastructure, the diffusion of innovation and coordinated policies that create more favourable conditions for reducing emissions (Wang et al. 2022). But population itself can exacerbate environmental pressures by increasing resource demand and energy consumption, highlighting the need for strategic governance to counteract these effects (Du et al. 2023). Beyond structural inequalities, institutional frameworks and regional policies are crucial in determining the environmental impact of digitalisation. As industrial upgrading and better environmental governance require active policy intervention, their ability to drive green transformation in less developed regions depends on regulatory support (Wang et al. 2022). Targeted sustainability policies, such as carbon trading schemes and sector-specific incentives, are crucial for translating digital breakthroughs into real emission reductions in highly industrialised areas, where digital growth alone is insufficient to limit emissions. These outcomes are further shaped by the urban dimension: higher-density areas tend to benefit more from the decarbonisation effects of digitalisation due to improved infrastructure, the diffusion of innovation and coordinated policies that create more favourable conditions for reducing emissions (Wang et al. 2022). But population itself can exacerbate environmental pressures by increasing resource demand and energy consumption, highlighting the need for strategic governance to counteract these effects (Du et al. 2023).

In addition, the relationship between digitalisation and environmental sustainability is not straightforward. Although digital tools can enhance efficiency and expedite the shift to low-carbon systems, their widespread adoption frequently results in temporary rises in energy use and emissions. The proliferation of digital infrastructure and data centres can create substantial electricity consumption, indicating that digitalisation may initially increase emissions before the realisation of efficiency improvements and structural transformations (Cheng et al. 2023). Furthermore, the environmental impact is context-dependent: in areas dependent on fossil fuel energy systems or characterised by carbon-intensive industrial frame-

works, the advantages of digitalisation are more constrained, whereas in cleaner or more innovative economies, the same technologies can enhance decarbonisation efforts. Institutional arrangements also influence outcomes, as the beneficial impact of digitalisation is more pronounced in environments where public frameworks effectively direct technological adoption towards sustainability objectives (Sun and Kim 2021).

4.3 Data and methodology

4.3.1 Data and description

The analysis includes 226 NUTS-2 regions of the European Union, based on the 2016 regional classification[3]. The dependent variable, reflecting emissions dynamics, is the rate of increase in per capita CO_2 emissions (*GHGgrowth*). This aligns with earlier research on emissions trends and their drivers (Friedlingstein et al. 2014; Jiang and Guan 2016). Rather than focusing on absolute levels, we employ a logarithmic adjustment to capture proportional changes across regions. This choice allows us to compare dynamics across territories of very different sizes and emission levels, ensuring that relative changes carry the same weight regardless of whether they occur in high- or low-emission regions. In this way, the measure reflects the intensity of emission growth in a scale-independent manner and avoids results being driven by a few large emitters.

To measure digitalisation, we use the spread of internet access and the quality of the connection. The first dimension (*InternetAccess*) is in line with previous research, which frequently uses internet access as a crucial sign of digitalisation (Asongu et al. 2018; Sun and Kim 2021) to capture the extent to which digital infrastructure is integrated into everyday life. Internet access plays a key role in facilitating digital interactivity, driving new technology adoption, and potentially

[3]Commission Regulation (EU) 2016/2066 of 21 November 2016 amending the annexes to Regulation (EC) No 1059/2003 of the European Parliament and of the Council on the establishment of a common classification of territorial units for statistics (NUTS). Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R2066

influencing environmental performance. The second dimension (*ConnectionQuality*) is represented by the upload speed, as it offers a more precise representation of the technological capacity of enterprises in comparison to download speed. Upload speed is connected to numerous business functions, facilitating cloud computing, teleconferencing, and the delivery of digital services – essential components in a digital economy (Tranos et al. 2024). All independent variables refer to the year 2019.

In developing our model, we selected control variables based on existing literature. The transportation sector is recognised as one of the most carbon-intensive industries, with road freight transport as a major contributor to CO_2 emissions (Demir et al. 2015; Zhu and Lan 2023), so we control by the logarithm of national road freight transport by region of loading (*log(Transport)*). The analysis also incorporates the share of gross value added from energy-intensive sectors[4] (*EnergyIntensiveGVA*). Energy-intensive industries are recognised for their role in emissions due to their significant energy consumption and carbon-intensive production methods (Yuan and Zhao 2016; Du et al. 2018). Demographic differences between regions are accounted by the logarithm of population size (*log(Population)*). The scale of human presence serves as a critical factor in the anthropogenic footprint, which is closely linked to increased energy demand, consumption of goods and services, and resource use, all of which play a significant role in the emissions growth (Cheng et al. 2023; Wu et al. 2023). Regional gross domestic product per capita (*GDP_pc*) is included as a control variable, as economic activity plays a key role in shaping CO_2 emissions. Higher levels of GDP are generally associated with increased energy consumption and carbon emissions (Lane 2011; Azevedo et al. 2018). At the same time, increased economic scale can facilitate investment in cleaner technologies and improve production processes, which can help mitigate some of the emissions impacts.

Heating degree days (*HDD*) is also used as a control. Empirical evidence suggests that variations in HDD are closely linked to emissions dynamics, as reductions in

[4]The energy-intensive sectors included in this measure are: Mining and quarrying; Manufacturing; Electricity, gas, steam and air conditioning supply; Water supply, sewerage, waste management and remediation activities.

heating needs can lead to lower CO_2 emissions, while increased heating demand intensifies energy consumption (Zhang and Zhou 2019). The percentage of SMEs that introduce product innovations (*ProdInnovation*) is used as a proxy for innovation. Technological developments can promote the adoption of cleaner production techniques and increase efficiency, but they can also encourage industrial expansion, which may result in increased emissions (Chen and Lei 2018; Mensah et al. 2018). We finally include the logarithm of CO_2 emissions per capita for 2019 ($log(CO_2)$). In fact, regions with higher baseline emissions may face greater regulatory pressure or stricter policies to reduce carbon production, which could affect subsequent emissions trends.

The data used in this study come from multiple sources. The Annual Regional Database of the European Commission[5] provides data on several key variables. Per capita CO_2 emissions are measured in metric tonnes, while GDP at current market prices and *EnergyIntensiveGVA* are expressed in million euros and as a percentage of total GVA, respectively. Additionally, *Population* is reported as the total number of residents on 1st January 2019. Eurostat[6] provides data on *InternetAccess*, expressed as the percentage of households with an internet connection, and *Transport*, measured in thousand tonnes. The original data for this variable were available at NUTS-3 level and have been aggregated to NUTS-2 level to maintain consistency with the rest of the dataset. *HDD* is expressed in degree days and represents the cumulative difference between the daily mean temperature and a predefined base temperature over a given period, capturing annual variations in heating demand. Other sources complement these datasets: *ConnectionQuality*, represented by average upload speed (Mbps), is obtained from the European Data Journalism Network[7]. Innovation is measured through the percentage of SMEs introducing product innovations (*ProdInnovation*), based on the Regional Innovation Scoreboard[8]. Due to missing values, an interpolation

[5]European Commission, Joint Research Centre (JRC). *Annual Regional Database of the European Commission (ARDECO)*. Available at https://urban.jrc.ec.europa.eu/ardeco/explorer?lng=en

[6]Eurostat. *Regional Database*. Available at https://ec.europa.eu/eurostat/web/regions/database

[7]European Data Journalism Network (EDJNet). Available at https://github.com/EDJNet

[8]European Commission. *Regional Innovation Scoreboard*. Available at https://projects.research-and-innovation.ec.europa.eu/en/statistics/performance-indicators/

method was applied to *InternetAccess* and *ProdInnovation*, as detailed in the following section. Table 4.1 presents the descriptive statistics of the variables used in the analysis[9].

Table 4.1: Summary statistics.

Variable	Obs.	Mean	SD	Min	Max
GHGgrowth	226	-0.04177	0.09344	-0.60493	0.19655
InternetAccess	226	88.69908	6.71238	67.61051	100.00000
ConnectionQuality	226	28.87057	22.93443	2.09000	123.39000
log(Transport)	226	10.44000	1.78795	-11.51000	12.30000
EnergyIntensiveGVA	226	0.23209	0.09711	0.04209	0.62832
log(Population)	226	14.16000	0.85318	10.30000	16.32000
GDP_pc	226	0.02997	0.01490	0.00550	0.08379
HDD	226	2506.947	841.989	397.240	6421.790
ProdInnovation	226	0.48448	0.24472	0.00000	0.95618
$log(CO_2)$	226	2.09960	0.50072	0.51160	3.98370

In addition to basic summary statistics, we explore the spatial distribution of the key variables through the Global Moran's I statistic. The results, reported in Table 4.2, indicate significant positive spatial autocorrelation for *GHGgrowth*, *InternetAccess*, and *ConnectionQuality*. The spatial concentration of these conditions is further illustrated by the LISA cluster maps in Figures 4.3a -4.3c, which highlight local clusters of high and low values across EU regions.

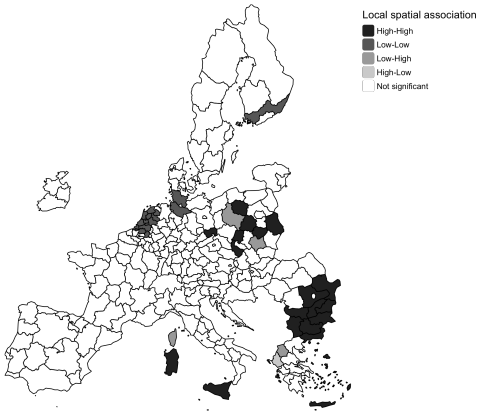
Table 4.2: Global Moran's I.

Variable	Moran's I	p-value
GHGgrowth	0.1858	2.497e-05
InternetAccess	0.6548	2.2e-16
ConnectionQuality	0.6282	2.2e-16

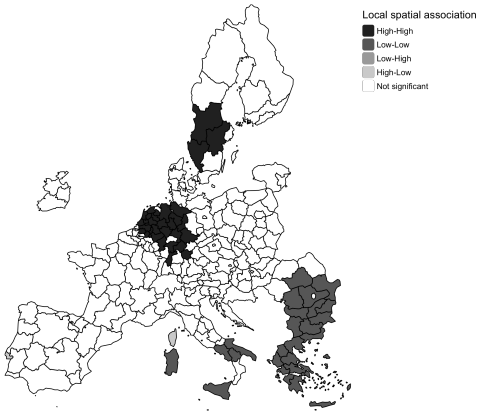
`european-innovation-scoreboard/eis-2024#/ris`

[9]To avoid undefined values for observations with *Transport* = 0, a small constant (0.00001) was added before the log transformation of *Transport*. The resulting minimum reflects this adjustment.

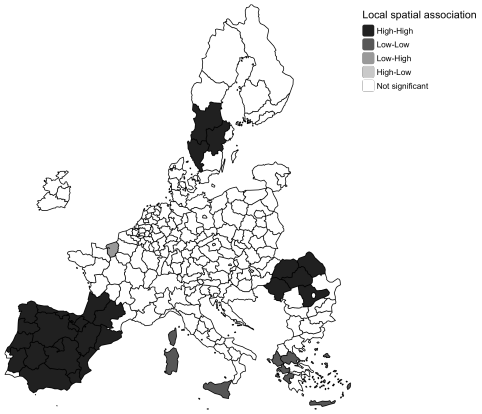
Figure 4.3: Local spatial clusters across European NUTS-2 regions.



(a) Local spatial clusters of *GHGgrowth*.



(b) Local spatial clusters of *InternetAccess*.



(c) Local spatial clusters of *ConnectionQuality*.

4.3.2 Imputation of missing data using Bayesian interpolation method

The Bayesian Interpolation Method (BIM; Benedetti and Palma 1994) was used to deal with missing data for variables *InternetAccess* and *ProdInnovation* at certain spatial units. The estimation was carried out for NUTS-2 regions where data are missing. Regions for which *InternetAccess* observations are obtained by BIM

include all regions in Germany[10], Greece[11], and Poland[12], for a total of 68 NUTS-2 regions. *ProdInnovation* BIM estimates are used to cover regions of Austria[13], Belgium[14], and selected regions in France[15], summing up a total of 34 NUTS-2 regions for which data are now integrated.

BIM estimates allow us to cover a wider range of regions and estimate our model. The presence of missing data is a challenge in environmental and technological models specified over NUTS-2 regions of Europe. However, in presence of spatial effects throughout the Continent, we find preferable using interpolation techniques that subsume the presence of spatial effects. Spatial imputation for missing data is a well-known problem in statistical and econometric analyses (Tobler and Kennedy 1985). Despite several techniques can be opted, in this paper we focus on BIM due to two features. First, BIM estimates assume that the data-generating process underlying spatial realisation is a conditional autoregressive process and it can therefore consider potential autocorrelation. Second, BIM estimates can be used to impute missing data or disaggregate variables to preserve pycnophylactic property[16].

BIM assumes that spatial process at the disaggregated level follows a multivariate normal distribution, with spatial structure incorporated through a conditional autoregressive (CAR) model (Besag 1974). With $\mathbf{Z} = (\mathbf{Z}_1, \ldots, \mathbf{Z}_n)^t$ the original process at lower spatial scale and $\mathbf{Z}^* = (\mathbf{Z}_1^*, \ldots, \mathbf{Z}_m^*)^t$ the derived process at the aggregate spatial scale for which data are available, we can specify the posterior

[10]Baden-Württemberg, Bavaria, Berlin, Brandenburg, Bremen, Hamburg, Hesse, Mecklenburg-Vorpommern, Lower Saxony, North Rhine-Westphalia, Rhineland-Palatinate, Saarland, Saxony, Saxony-Anhalt, Schleswig-Holstein, Thuringia

[11]Macedonia, Thrace, Epirus, Thessaly, Ionian Islands, Western Greece, Central Greece, Peloponnese, Attica, Crete

[12]Łódzkie, Mazowieckie, Małopolskie, Śląskie, Lubelskie, Podkarpackie, Świętokrzyskie, Podlaskie, Wielkopolskie, Zachodniopomorskie, Lubuskie, Dolnośląskie, Opolskie, Kujawsko-Pomorskie, Warmińsko-Mazurskie, Pomorskie

[13]Burgenland, Lower Austria, Vienna, Carinthia, Styria, Upper Austria, Salzburg, Tyrol, Vorarlberg

[14]Brussels-Capital, Flemish Region, Walloon Region

[15]Normandy, Brittany, Centre-Val de Loire, Île-de-France, Bourgogne-Franche-Comté, Grand Est, Hauts-de-France, Pays de la Loire, Nouvelle-Aquitaine, Occitanie, Auvergne-Rhône-Alpes, Provence-Alpes-Côte d'Azur, Corsica

[16]Ensuring that the estimated values, when aggregated via the transformation matrix $\boldsymbol{G}$, replicate the derived observed data.

distribution of $\mathbf{Z}$ given $\mathbf{Z}^*$ as:

$$P(\mathbf{Z} \mid \mathbf{Z}^*) \propto P(\mathbf{Z})P(\mathbf{Z}^* \mid \mathbf{Z}) \tag{4.1}$$

. Under the CAR specification, the prior distribution is:

$$\mathbf{Z} \sim \mathbf{MVN}(\boldsymbol{\mu}, (\mathbf{I} - \rho\mathbf{C})^{-1}\sigma^2) \tag{4.2}$$

where $\boldsymbol{\mu}$ is the vector of prior means, ρ is a scalar parameter capturing spatial autocorrelation, $\mathbf{C}$ the proximity matrix and σ^2 is the process variance. The aggregated values can be expressed as a linear transformation of the disaggregated ones: $Z^* = GZ$, where G is the aggregation matrix (see, Panzera and Postiglione 2014). Thus, the conditional distribution of Z^* given Z can be rewritten as:

$$\mathbf{Z}^* \mid \mathbf{Z} \sim MVN(\mathbf{G}\boldsymbol{\mu},\, \mathbf{G}\boldsymbol{\Sigma}_{\mathbf{Z}}\mathbf{G}^t) \tag{4.3}$$

Combining equations (4.1) and (4.3), the posterior distribution of the disaggregated process is:

$$\mathbf{Z} \mid \mathbf{Z}^* \sim MVN(\hat{\mathbf{Z}}, \mathbf{V}_{\hat{\mathbf{Z}}}) \tag{4.4}$$

with:

$$\mathbf{V}_{\hat{\mathbf{Z}}} = \left[\mathbf{G}^t \left(\mathbf{G}\frac{(\mathbf{I} - \rho\mathbf{C})}{\sigma^2}\mathbf{G}^t\right)^{-1} \mathbf{G} + \frac{(\mathbf{I} - \rho\mathbf{C})}{\sigma^2}\right] \tag{4.5}$$

$$\hat{\mathbf{Z}} = \mathbf{V}_{\hat{\mathbf{Z}}}\left[\frac{(\mathbf{I} - \rho\mathbf{C})}{\sigma^2}\boldsymbol{\mu} + \mathbf{G}^t \left(\mathbf{G}\frac{(\mathbf{I} - \rho\mathbf{C})}{\sigma^2}\mathbf{G}^t\right)^{-1} \mathbf{Z}^*\right] \tag{4.6}$$

. The prior mean vector $\boldsymbol{\mu}$ can be estimated via linear model using auxiliary variables available at both spatial levels (*i.e.*, NUTS-2 and NUTS-1) as a support. The Ordinary Least Squares solutions at NUTS-1 offers parameters to estimate the set $\boldsymbol{\mu}$ of means to be used to interpolate observations for the original process are. Plus, the residual variance from this regression can be used to estimate σ^2 in (4.5) and (4.6). Following previous literature (Cartone and Panzera 2021), we set the $\rho = 0.30$. The proximity matrix $\mathbf{C}$ whose entries are non-zero elements only if two units are considered and the main diagonal is zero by definition. Estimates

from (4.5) and (4.6) can be improved to maintain the pycnophylactic property:

$$\tilde{\mathbf{Z}} = \hat{\mathbf{Z}} + \mathbf{V}_{\hat{\mathbf{Z}}}\mathbf{G}^t \left[\mathbf{G}\mathbf{V}_{\hat{\mathbf{Z}}}\mathbf{G}^t\right]^{-1} (\mathbf{Z}^* - \mathbf{G}\mathbf{Z}) \tag{4.7}$$

$$\mathbf{V}_{\tilde{\mathbf{Z}}} = \mathbf{V}_{\hat{\mathbf{Z}}} - \mathbf{V}_{\hat{\mathbf{Z}}}\mathbf{G}^t \left[\mathbf{G}\mathbf{V}_{\hat{\mathbf{Z}}}\mathbf{G}^t\right]^{-1} \mathbf{G}\mathbf{V}_{\hat{\mathbf{Z}}} \tag{4.8}$$

In essence, BIM estimates are used to interpolate data unavailable at lower spatial levels while preserving pycnophylactic and spatial variability typical of geographically distributed data.

4.3.3 Model specifications

We estimate three different model specifications. In all cases, the dependent variable is the regional growth rate per capita CO_2 emissions between 2019 (t_0) and 2022 (t_1), denoted as $GHGgrowth_{r,\,t_1-t_0}$. All the explanatory variables – including both digitalisation indicators and controls – are measured at the initial year t_0 (*i.e.*, 2019).

The first specification follows a linear model, where the relationship between digitalisation and emissions growth is assumed to be constant. The equation is formulated as follows:

$$\begin{aligned} GHGgrowth_{r,t1-t0} = \beta_0 + \beta_1 InternetAccess_{r,t0} + \beta_2 ConnectionQuality_{r,t0} \\ + \beta_k \mathbf{X}_{r,t0,k} + \varepsilon_r \end{aligned} \tag{4.9}$$

where $r = 1, \ldots, N$ represents the $N = 226$ regions, β_0 is the intercept, β_1 and β_2 capture the marginal effects of the regional diffusion of internet connectivity and the average upload speed as a measure of connection quality, respectively. $\mathbf{X}_{ik}$ is a vector of control variables. The error term ε_r captures unobserved factors affecting $GHGgrowth_{r,\,t_1-t_0}$, with zero mean and variance σ^2_ε. To assess whether the relationship between digitalisation and the environment is non-linear (Kopp et al. 2023; Ma et al. 2025), we estimate a second model by introducing quadratic

terms in digitalisation variables:

$$\begin{aligned} GHGgrowth_{r,t1-t0} = \beta_0 &+ \beta_1 InternetAccess_{r,t0} + \beta_2 InternetAccess^2_{r,t0} \\ &+ \beta_3 ConnectionQuality_{r,t0} + \beta_4 ConnectionQuality^2_{r,t0} \\ &+ \beta_k \mathbf{X}_{r,t0,k} + \varepsilon_r \end{aligned} \tag{4.10}$$

The inclusion of squared terms allows to account for potential non-linearities in the relationship between digitalisation and emission growth. These may arise when the environmental impact changes across levels of digital development: at lower levels, improvements in digital connectivity might reduce emissions through efficiency gains and behavioural shifts, while at higher levels, increased usage and energy demand may offset those benefits. However, digitalisation may initially contribute to higher emission growth, before enabling structural transformations that support decarbonisation.

Finally, a third specification introduces an interaction term between digitalisation dimensions. In this model, *InternetAccess* is replaced by a dummy variable (*AccessLevel*), equal to 1 if the region's internet access is above the mean, and 0 otherwise. Additionally, an interaction term between this dummy and *ConnectionQuality* is introduced:

$$\begin{aligned} GHGgrowth_{r,t1-t0} = \alpha_0 &+ \beta_1 AccessLevel_{r,t0} + \beta_2 ConnectionQuality_{r,t0} \\ &+ \beta_3 AccessLevel_{r,t0} * ConnectionQuality_{r,t0} \\ &+ \beta_k \mathbf{X}_{r,t0,k} + \varepsilon_r \end{aligned} \tag{4.11}$$

Unlike the quadratic specification, this model does not assume a continuous variation in marginal effects. Rather, it examines whether the effect of connection quality varies between two separate digital environments – low and high access. The interaction term enables the evaluation of whether improvements in infrastructure (with regard to speed) yield varying environmental consequences based on the existing level of access. This method incorporates distinct contextual variability, wherein the same changes in connection quality may produce different outcomes

in areas with different baseline circumstances. Incorporating both continuous (squared terms) and regime-dependent (interaction) forms of non-linearity in our study facilitates a more nuanced understanding of how digitalisation affects environmental outcomes.

4.3.4 Econometric strategy

Analysing the environmental impact of digitalisation requires methodological approaches that can capture both average effects across regions and possible heterogeneity, whether across the distribution of emission growth or across geographical space. As a starting point, we employ an OLS regression, which provides a global benchmark. This approach assumes a uniform relationship between digitalisation and emissions growth across all regions, with each covariate associated with a single coefficient representing its average marginal effect. While OLS provides a useful overview, it overlooks two critical sources of heterogeneity: variation in effects across the distribution of the dependent variable and potential differences in spatial contexts.

We adopt two complementary frameworks that relax the global model assumptions. First, we account for distributional heterogeneity by applying QR. In contrast to OLS, which emphasises the conditional mean, QR allows the estimation of effects at many places within the conditional distribution (Koenker and D'Orey 1987). This approach aligns with a growing number of studies that adopt quantile regression to investigate the environmental implications of digitalisation in differentiated contexts (e.g., Wei and Ullah 2022). Let Y_i represent the dependent variable and $\mathbf{X}_i$ the vector of explanatory variables, the model estimates the conditional quantile function:

$$Q_Y(\tau \mid \mathbf{X}_i) = \mathbf{X}_i' \boldsymbol{\beta}_\tau \tag{4.12}$$

for a given quantile level $\tau \in (0, 1)$, where β_τ captures the quantile-specific coefficients. As proposed by Buchinsky 1998, the model can also be expressed as:

$$Y_i = \mathbf{X}_i' \boldsymbol{\beta}_\tau + u_{\tau,i} \tag{4.13}$$

with $u_{\tau,i}$ denoting the quantile-specific residuals, such that the τ-th quantile of $u_{\tau,i}$, conditional on $\mathbf{X}_i$, is zero. The Least Absolute Deviation estimator of β_τ is obtained by solving the following minimisation problem.

$$\min_{\boldsymbol{\beta}_\tau} \frac{1}{n} \left\{ \left(\sum_{i:\, Y_i \geq \mathbf{X}_i' \boldsymbol{\beta}_\tau} \tau \left| Y_i - \mathbf{X}_i' \boldsymbol{\beta}_\tau \right| \right) + \left(\sum_{i:\, Y_i < \mathbf{X}_i' \boldsymbol{\beta}_\tau} (1-\tau) \left| Y_i - \mathbf{X}_i' \boldsymbol{\beta}_\tau \right| \right) \right\} \quad (4.14)$$

Although the objective function is not linear, the problem is solved using linear programming. Unlike linear models that yield a singular estimate of average effects, QR generates a series of coefficients illustrating how the influence of each covariate varies over the outcome distribution. This facilitates the identification of diverse patterns, encompassing non-linear or asymmetric correlations that would be hidden in mean-based models. The approach is semi-parametric, robust to outliers and heteroskedasticity, and does not impose distributional assumptions on the error term. Specifically, it models the conditional distribution via a set of linear functions estimated at various quantile levels, providing a comprehensive description of the association between variables and the outcome variable across its whole range (Cartone et al. 2021).

Second, OLS estimation overlooks potential geographical non-stationarity, where correlations vary across locations due to differences in economic structures, environmental policies, or rates of technology adoption, and is potentially misleading (Anselin 1988; Gutiérrez Posada et al. 2018). Despite QR enhancing OLS by identifying heterogeneous effects across the distribution of the dependent variable, it still functions as a global method and, as to OLS, presumes geographic homogeneity. To explicitly account for regional heterogeneity, we employ GWR (Fotheringham et al. 2002).

GWR is a non-parametric method that allows for geographical non-stationarity by allowing regression coefficients to vary between locations rather than assuming a uniform worldwide relationship. Rather than applying a trend surface over the entire study area, GWR calculates local parameters for each observation,

providing a spatially detailed representation of the relationships under investigation (Brunsdon et al. 1996). Each regression is estimated locally, producing region-specific coefficients that illustrate the different effects of explanatory variables on emissions growth in different spatial contexts (Brunsdon et al. 1998). Our model can be written in the case of GWR as:

$$Y_i = \beta_{i0} + \beta_{i1}x_{i1} + \beta_{i2}x_{i2} + \cdots + \beta_{ik}x_{ik} + \varepsilon_i \quad \text{with} \quad \varepsilon_i \sim N(0, \sigma^2) \tag{4.15}$$

A local regression is estimated at each point i using a sample of spatial units within a specified bandwidth, generating a specific set of parameters for each region, calculated as follows:

$$\hat{\beta}_i = (X'\mathbf{W}_i X)^{-1} X'\mathbf{W}_i Y \tag{4.16}$$

The choice of bandwidth is essential as it determines the extent of the local neighbourhood used for each estimation. Various criteria exist for selecting the optimal bandwidth, such as the Akaike Information Criterion (AIC), which aims to minimise information loss, and the Cross-Validation Score (CVS), which seeks to minimise the sum of squared errors. This study uses a cross-validation method to identify the optimal bandwidth. The weighting matrix $\mathbf{W}_i$ is a diagonal matrix that assigns different weights to observations according to their spatial proximity. It takes the following form:

$$\mathbf{W}_i = \begin{bmatrix} \alpha_{i1} & 0 & 0 & \cdots & 0 \\ 0 & \alpha_{i2} & 0 & \cdots & 0 \\ 0 & 0 & \alpha_{i3} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & \alpha_{iN} \end{bmatrix} \tag{4.17}$$

α_{ij} denotes the weight assigned to observation j in the local regression analysis of observation i. Proximity is associated with similarity, leading to a decrease in weights as distance increases. Several kernel functions can be used to represent this decay. In this study, a Gaussian kernel is used, defined as follows:

$$\alpha_{ij} = e^{-\frac{1}{2}\left(\frac{d_{ij}}{h}\right)^2} \tag{4.18}$$

where d_{ij} is the distance between observations i and j and h is the bandwidth. This specification guarantees a gradual reduction of the weights as the distance increases, thus avoiding sudden discontinuities in the influence of the observations. In addition to its ability to account for spatially varying interactions, the GWR has other advantages. It can account for local fixed effects as each region has its own intercept (Partridge et al. 2008). It has also been shown to reduce spatial autocorrelation in residuals when coefficients are heterogeneous (Fotheringham et al. 2002).

4.4 Results

The OLS results in Table 4.3 offer an initial assessment of the relationship between digitalisation and changes in per capita CO_2 emissions from 2019 to 2022. In the linear specification (Column a), a higher share of households with internet access corresponds with reduced emissions growth, however the effect is only marginally significant, whilst the *ConnectionQuality* coefficient is negative but lacks statistical significance. This basic model provides a useful reference point but has limitations in its capacity to capture the complex nature of the digital-environment relationship.

The quadratic specification (Column (b)) offers the best representativeness among the models estimated by standard OLS and indicates that digitalisation is not uniform but varies by the degree of digital development. Both parameters corresponding to *InternetAccess* and *ConnectionQuality* exhibit convex relationships: at lower levels, improvements correspond to slower emissions growth, although the marginal decarbonisation benefit progressively diminishes as access and speed increase. For *InternetAccess*, this indicates that when connectivity remains limited, increasing household access might replace more resource-intensive activities. As connectivity becomes widespread, the efficacy of these gains diminishes, while the rising demand for energy-intensive activities – such as streaming, online services, and data traffic – may counterbalance earlier benefits, resulting in diminished overall impacts. For *ConnectionQuality*, the initial reductions in emissions growth

are consistent with the idea that faster upload speeds improve efficiency in business processes, promote the digitalisation of work practices, and diminish dependence on more carbon-intensive modes of production and interaction. However, as speeds continue to improve, the energy demands of advanced digital services, cloud computing, and high-definition content consumption increase, resulting in a diminished impact on mitigating emissions rise. This non-linearity has environmental implications, since it demonstrates the initial benefits of digitalisation, while subsequent phases of diffusion yield disparate environmental results.

The interaction model (Column (c)) corroborates this interpretation, as the impact of faster connections is dependent upon the degree of household access. In areas with limited Internet access, improvements in connection quality correspond with a reduction in emissions growth, indicating efficiency advantages from digitalisation. In places with above-average Internet access, the interaction term becomes positive, indicating that the advantages of increased speeds diminish and may even be nullified when access is prevalent. The environmental impact of digitalisation depends not only on each component separately but also on their collective arrangement. Estimated parameters for the controls further support this interpretation. A higher percentage of SMEs implementing product innovation is linked to reduced emissions growth. The negative coefficient associated with GDP per capita suggests that more developed regions have superior capabilities to mitigate emissions increase, attributable to enhanced investment capacity, regulatory frameworks, or sectoral structures. Initial per capita emissions are inversely correlated with subsequent growth, aligning with increased need to mitigate in areas with previously elevated emissions. Finally, population is positively and significantly related to the dependent variable, showing that more populous regions experienced faster emissions growth over the period.

Table 4.3: Coefficients estimated for the three OLS specifications.

	Linear specification (a)	**Quadratic specification** (b)	**Interaction specification** (c)
Intercept	0.10250	-1.50700**	-0.08120
	(0.13920)	(0.03779)**	(0.48952)
InternetAccess	-0.00236*	-0.00378**	
	(0.00131)	(0.01770)**	
$InternetAccess^2$		0.00021**	
		(0.00010)**	
ConnectionQuality	-0.00038	-0.00187**	-0.00143***
	(0.00030)	(0.00083)**	(0.00607)***
$ConnectionQuality^2$		0.00002*	
		(0.00001)*	
*AccessLevel*ConnectionQuality*			0.00110**
			(0.07282)**
log(Transport)	0.00051	-0.00171	-0.00102
	(0.00449)	(0.00410)	(0.80337)
EnergyIntensiveGVA	0.05658	0.06281	0.09274**
	(0.06979)	(0.06921)	(0.20005)**
log(Population)	0.01296**	0.02246**	0.01623*
	(0.00929)**	(0.00969)**	(0.08331)*
GDP_pc	-1.22200**	-1.44400***	-2.18800***
	(0.63980)**	(0.63880)***	(0.00043)***
HDD	1.621e-06*	6.376e-06**	-1.253e-06*
	(8.035e-06)*	(8.252e-06)**	(0.87073)*
ProdInnovation	-0.08910***	-0.09777***	-0.08421***
	(0.03349)***	(0.03395)***	(0.01409)***
$log(CO_2)$	-0.02394**	-0.02226**	-0.02968**
	(0.01360)**	(0.01305)**	(0.02766)**
BP test	23.033	23.033	23.033
BP p-value	0.00612	0.01967	0.01053
R^2	0.27051	0.29256	0.27274

Standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Quantile regressions are introduced after performing a Breusch-Pagan test on the residuals of the three OLS model specifications, which confirmed the presence of heteroscedasticity. Table 4.4 shows the results for the linear specification, demonstrating a consistently negative and statistically significant correlation between

InternetAccess and emissions growth across all quantiles (Figure 4.4a), indicating that increased internet availability aids in reducing emissions growth throughout the distribution. The impact is especially significant in areas experiencing higher environmental challenges, where digital technologies might replace more resource-demanding tasks.

Figure 4.4b shows quantile curves for estimated parameters at different quantile levels (Cartone et al. 2021), particularly for *ConnectionQuality*. The figure illustrates that the coefficient for *ConnectionQuality* is most robust and statistically significant in the lower and central quantiles ($\tau = 0.2, 0.4, 0.5$), although it decreases and loses statistical significance at the upper quantile ($\tau = 0.8$). This suggests that boosts in upload speed are more impactful in locations with low to moderate emissions growth, whereas their marginal effect is less in areas experiencing high emissions pressures.

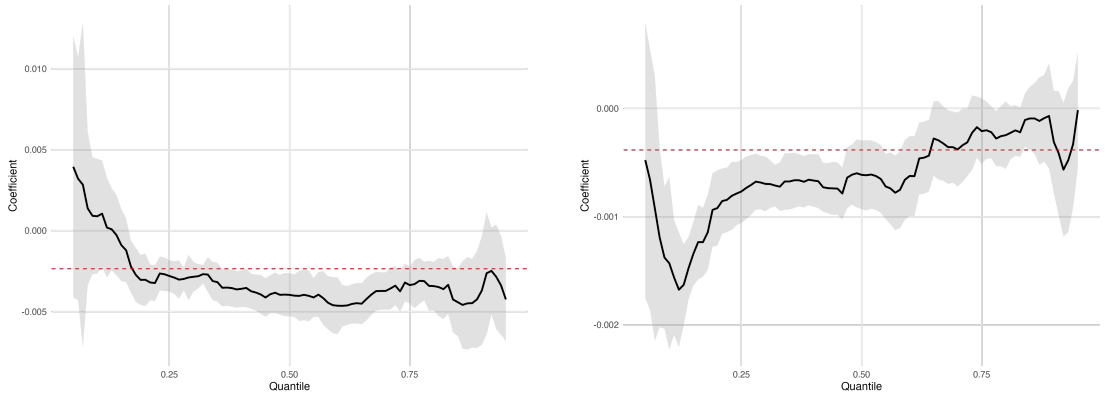
Table 4.4: Summary of QR for $\tau = 0.20$, 0.40, 0.50, 0.60, and 0.80 for the *linear specification*.

	0.20	**0.40**	**0.50**	**0.60**	**0.80**
Intercept	0.27317	0.21121	0.29725**	0.24495	0.19717
	(0.24590)	(0.19287)	(0.14302)	(0.27170)	(0.12625)
InternetAccess	-0.00305*	-0.00359***	-0.00397***	-0.00464***	-0.00343**
	(0.00162)	(0.00112)	(0.00133)	(0.00175)	(0.00150)
ConnectionQuality	-0.00092***	-0.00067***	-0.00061*	-0.00062*	-0.00025
	(0.00035)	(0.00024)	(0.00032)	(0.00037)	(0.00031)
log(Transport)	0.00048	0.00054	0.00127	0.00039	0.00258
	(0.03182)	(0.02085)	(0.00423)	(0.03020)	(0.03741)
EnergyIntensiveGVA	0.10072	0.10755**	0.04279	0.05495	0.00321
	(0.07599)	(0.05409)	(0.06033)	(0.06242)	(0.08575)
log(Population)	0.00525	0.01002	0.00703	0.01523	0.00925
	(0.02992)	(0.02183)	(0.00939)	(0.02950)	(0.02877)
GDP_pc	-1.05594	-0.18787	-0.15688	-0.05217	-0.80680
	(0.71598)	(0.58468)	(0.69060)	(0.57230)	(0.59639)
HDD	-0.000001	0.000001	-0.000003	-0.000002	0.000001
	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)
ProdInnovation	-0.09976***	-0.13392***	-0.11841***	-0.11081***	-0.10030***
	(0.03006)	(0.02602)	(0.03326)	(0.04135)	(0.03555)
log(CO_2)	-0.03720**	-0.01658	-0.00941	-0.00539	0.01955*
	(0.01785)	(0.01457)	(0.01375)	(0.02242)	(0.01725)
Pseudo R^2	0.21796	0.24138	0.23748	0.22943	0.23548

Standard errors in parentheses.

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

Figure 4.4: Quantile regression coefficients for the *linear specification*.



(a) *InternetAccess* quantile regression coefficients.

(b) *ConnectionQuality* quantile regression coefficients.

Solid lines represent the linear and squared terms for each digital variable across quantiles; shaded areas indicate 95% confidence intervals. The horizontal dashed line corresponds to the OLS estimate.

The results for the QR using the quadratic specification (Table 4.5) indicate that the evidence for *InternetAccess* is mostly concentrated in the central part of the distribution. The linear term is negative across all quantiles but statistically significant only in the middle range, whereas the squared term is consistently positive and significant within the same interval (Figures 4.5a and 4.5b). This pattern aligns with the convex profile already observed in the OLS results; however, the quantile regressions reveal that significance is not uniform: the mitigating effect of broader access manifests only in regions with moderate emissions growth. In low-growth contexts, substitution effects may be fully exploited, while in high-growth areas, other factors – such as industrial activity or demographic pressures – predominate, overshadowing the influence of digital diffusion.

The pattern for *ConnectionQuality* extends over a broader range of quantiles (Figures 4.5c and 4.5d). The linear coefficient is negative and significant from the lower to the central quantiles, while the squared term is positive and significant. This finding is consistent with the OLS results; nevertheless, the quantile regressions show that the most substantial decreases in emissions growth occur at the central quantiles ($\tau = 0.4$ and $\tau = 0.6$), where the coefficients exhibit the highest absolute

values. At the lowest quantile ($\tau = 0.2$), the effect remains negative and statistically significant, although its magnitude is reduced, indicating that improvements in speed have a more limited impact where emissions growth is already low. At higher quantiles, the benefits decline, reflecting the increased energy consumption associated with advanced digital services and the growing importance of other structural factors.

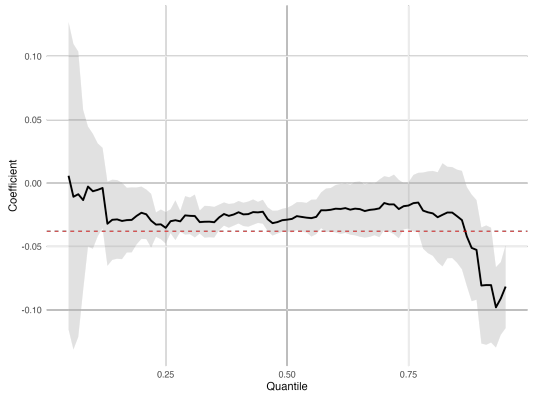
Table 4.5: Summary of QR for $\tau = 0.20$, 0.40, 0.50, 0.60, and 0.80 for the *quadratic specification.*

	0.20	**0.40**	**0.50**	**0.60**	**0.80**
Intercept	1.10762	1.03138***	1.20188***	0.81459	1.02926
	(0.9284)	(0.3522)	(0.3713)	(0.6573)	(1.3551)
InternetAccess	-0.02340	-0.02299**	-0.02884***	-0.02019*	-0.02388*
	(0.0206)	(0.0089)	(0.0094)	(0.0187)	(0.0335)
$InternetAccess^2$	0.00012	0.00011**	0.00015**	0.00010	0.00012
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0002)
ConnectionQuality	-0.00288***	-0.00297***	-0.00321***	-0.00329**	-0.00096*
	(0.0007)	(0.0006)	(0.0005)	(0.0014)	(0.0029)
$ConnectionQuality^2$	0.00002***	0.00003***	0.00003***	0.00003*	0.00001
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
log(Transport)	0.00977***	-0.00125	-0.00260	-0.00133	0.00163
	(0.0029)	(0.0019)	(0.0057)	(0.0040)	(0.0573)
EnergyIntensiveGVA	0.06791	0.07088	0.06174	0.06004	-0.02564
	(0.0526)	(0.0435)	(0.0455)	(0.0688)	(0.1004)
log(Population)	0.00365	0.01521***	0.02141***	0.02182	0.01264
	(0.0057)	(0.0055)	(0.0069)	(0.0358)	(0.0526)
GDP_pc	-1.44459**	-1.36206**	-0.30670	-0.54139	-0.64273
	(0.5633)	(0.5534)	(0.5361)	(0.7166)	(0.8833)
HDD	0.00000	0.00000	0.00003	0.00000	0.00000
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
ProdInnovation	-0.07702**	-0.08871***	-0.13550***	-0.10140***	-0.11788***
	(0.0273)	(0.0160)	(0.0214)	(0.0309)	(0.0424)
$log(CO_2)$	-0.03815**	-0.01795**	-0.00623	-0.00882	0.02519
	(0.0131)	(0.0086)	(0.0089)	(0.0185)	(0.0235)
Pseudo R^2	0.24605	0.27206	0.27776	0.26945	0.24573

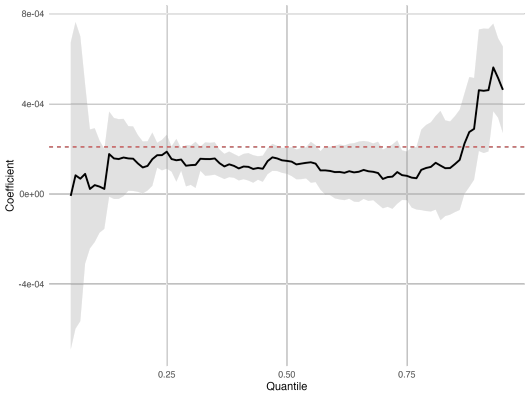
Standard errors in parentheses.

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

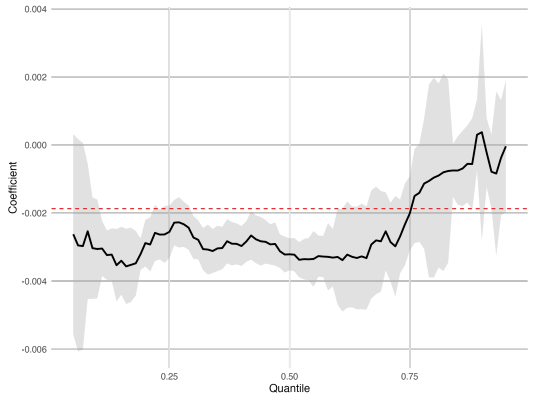
Figure 4.5: Quantile regression coefficients for the *quadratic specification*.



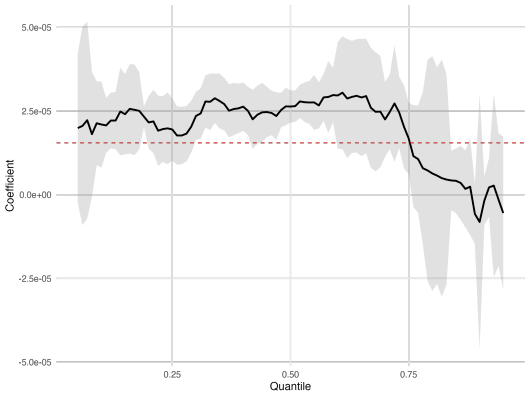
(a) *InternetAccess* quantile regression coefficients.



(b) $InternetAccess^2$ quantile regression coefficients.



(c) *ConnectionQuality* quantile regression coefficients.



(d) $ConnectionQuality^2$ quantile regression coefficients.

Solid lines represent the linear and squared terms for each digital variable across quantiles; shaded areas indicate 95% confidence intervals. The horizontal dashed line corresponds to the OLS estimate.

Table 4.6 presents the quantile-specific estimates for the *interaction specification*. *ConnectionQuality* exhibits a negative and statistically significant correlation across all quantiles, with a stronger effect at the lower and central parts of the distribution. This suggests that enhancements in speed generally facilitate decarbonisation, particularly in areas with relatively low or moderate emissions growth.

The interaction term with *AccessLevel* is positive and statistically significant at

$\tau = 0.2, 0.5$, and 0.6. In areas where household internet access exceeds the average, the decarbonising impact of faster connections is substantially diminished. At the median quantile, the combined effect of *ConnectionQuality* and the interaction is almost imperceptible, whereas in areas with limited access the coefficient for *ConnectionQuality* remains significantly negative across the distribution. Overall, the results indicate that increases in speed are most effective in reducing emissions growth where internet access is limited; in well-connected places, the environmental benefits of faster connections are largely offset.

Table 4.6: Summary of QR for $\tau = 0.20$, 0.40, 0.50, 0.60, and 0.80 for the *interaction specification.*

	0.20	**0.40**	**0.50**	**0.60**	**0.80**
Intercept	-0.07878	-0.06705	0.03207	0.02066	0.03123
	(0.1732)	(0.1803)	(0.2065)	(0.2446)	(0.1211)
AccessLevel	-0.03861*	-0.03687*	-0.05899***	-0.06329***	-0.03861*
	(0.0207)	(0.0203)	(0.0213)	(0.0230)	(0.0209)
ConnectionQuality	-0.00266***	-0.00165**	-0.00191***	-0.00148**	-0.00144**
	(0.0004)	(0.0009)	(0.0006)	(0.0007)	(0.0006)
*AccessLevel*ConnectionQuality*	0.00196***	0.00145*	0.00185**	0.00143*	0.00108
	(0.0005)	(0.0010)	(0.0007)	(0.0008)	(0.0008)
log(Transport)	-0.00145	-0.00045	0.00193	0.00183	0.00325
	(0.0318)	(0.0355)	(0.0344)	(0.0351)	(0.0358)
EnergyIntensiveGVA	0.18678***	0.17616**	0.12334*	0.12609*	0.00586
	(0.0631)	(0.0865)	(0.0739)	(0.0805)	(0.0713)
log(Population)	0.01683*	0.01348	0.00556	0.00726	0.00574
	(0.0306)	(0.0339)	(0.0345)	(0.0372)	(0.0314)
GDP_pc	-2.72002***	-1.73207**	-1.31673**	-0.94310*	-1.14181**
	(0.4752)	(0.6751)	(0.6301)	(0.7006)	(0.5432)
HDD	0.00000	0.00000	-0.00000*	-0.00001*	-0.00001
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
ProdInnovation	-0.04674*	-0.08382***	-0.10039***	-0.09378**	-0.10891***
	(0.0223)	(0.0319)	(0.0338)	(0.0375)	(0.0269)
log(CO_2)	0.05122***	-0.03175*	-0.02333*	-0.02264*	0.00740
	(0.0188)	(0.0164)	(0.0198)	(0.0234)	(0.0177)
Pseudo R^2	0.22328	0.22865	0.22553	0.22552	0.23327

Standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 4.7 presents the results of the GWR estimation for the simple specification, without interaction or quadratic terms. The GWR produces 226 regional estimates for each parameter. Compared with the global OLS, the GWR provides a significantly better fit, with an R^2 of 0.4379. The F-tests proposed by Leung et al. 2000 are used to assess model efficiency and spatial non-stationarity. The F1 statistic evaluates the residual sum of squares (RSS) between the OLS and GWR models; a value significantly less than one indicates that the GWR provides a better fit. The F2 statistic measures the absolute improvement in RSS, although it is not significant in our case. The F3 test assesses the spatial variability of each coefficient by comparing the observed variance with its expected distribution under spatial invariance. The test reveals substantial heterogeneity in several factors, such as *ConnectionQuality*, *log(Transport)*, *EnergyIntensiveGVA*, *log(Population)*, *HDD*, and *log(CO2_pc)*. The F4 test, which accounts for model complexity, further confirms the improved fit of the GWR specification.

A one-unit increase in *ConnectionQuality* (measured in Mbps) is associated with a variation in the annual growth rate of per capita CO_2 emissions between -0.18 and $+0.09$ percentage points across regions. This variation suggests that, although faster connections reduce emissions growth in many places, their impact is insignificant – or even positive – in others. The effect of a one-percentage-point increase in household connectivity (*InternetAccess*) ranges from -0.30 to $+0.02$ percentage points, with most coefficients being negative, indicating a generally beneficial role of digital diffusion in mitigating emissions growth. Several control variables also exhibit geographically distinct effects. Population correlates positively with emissions growth, although with significant variation in magnitude across regions, suggesting that scale effects are not spatially uniform. *ProdInnovation* generally mitigates emissions growth, although with varying intensity. Initial emissions show a primarily negative relationship, consistent with convergence dynamics; however, in some areas, this relationship weakens or even reverses, suggesting that past trajectories and structural constraints shape current adjustment patterns.

Table 4.7: Summary of GWR coefficient estimates for the *linear specification*.

	Min.	**1st Qu.**	**Median**	**3rd Qu.**	**Max.**	**F3 test**
Intercept	-1.07130	-0.61473	-0.30899	-0.07314	0.11730	+++
InternetAccess	-0.00298	-0.00137	-0.00061	0.00019	0.00110	
ConnectionQuality	-0.00181	-0.00101	-0.00048	-0.00004	0.00030	+++
log(Transport)	-0.07763	-0.03463	-0.01673	-0.00527	0.00080	+++
EnergyIntensiveGVA	-0.00270	0.01791	0.08931	0.18002	0.41520	+++
log(Population)	0.00794	0.02343	0.03759	0.06595	0.11700	+++
GDP_pc	-3.19320	-2.37880	-2.13460	-1.61790	-0.84540	
HDD	-0.000002	0.000007	0.00002	0.00003	0.00010	+++
ProdInnovation	-0.12291	-0.09016	-0.05427	-0.03848	-0.00760	
log(CO_2)	-0.06278	-0.01784	-0.00161	0.00711	0.01150	+++
R^2 *OLS*	0.27051					
R^2 *GWR*	0.43794					
F1 test	0.87261+					
F2 test	1.9611					
F4 test	0.77049					

+++ $p < 0.01$, ++ $p < 0.05$, + $p < 0.1$ (indicates global significance or significant spatial variability).

Figure 4.6a illustrates the spatial distribution of the local coefficients for *InternetAccess*. Negative associations with emissions growth are especially evident in regions of Eastern and Southern Europe, including South-West Bulgaria, Central Macedonia, South-Muntenia, and Sicily. In these regions, where household connectivity in 2019 was relatively low (often below 80%, see Figure 4.2b), improvements appear to have allowed behavioural changes – such as the adoption of remote work or online services – that replaced more carbon-intensive habits.

Negative effects are also observed in areas with already high household access, such as Friesland and Groningen in the Netherlands, Eastern and Midland in Ireland, and Northern and Eastern Finland, all exceeding 91% coverage. In these contexts, the explanation focuses less on the mere expansion of access and more on the surrounding system. The combination of low-carbon residential energy supply, service-oriented economic frameworks, and elevated digital literacy may facilitate additional advancements in household digitalisation, even in contexts of near-universal access. Conversely, in industrialised areas with similarly elevated

household access, such as Jihozápad in Czechia and Oberösterreich in Austria, the estimated coefficients are about zero or slightly positive. The significant presence of energy-intensive sectors (exceeding 30% of GVA in 2019) indicates that household digitalisation might interact with a carbon-intensive production base, thereby reinforcing energy-demanding processes instead of mitigating them.

Figure 4.6b shows the local coefficients for *ConnectionQuality*. The results reveal a more uniform pattern, with almost all coefficients being negative, indicating that enhancements in upload speed are typically linked to a deceleration in emissions growth. The most pronounced negative effects occur in areas with originally low speeds, like Burgenland, Lower Austria, and Styria, where average upload rates in 2019 were below 15 Mbps. Even slight enhancements in connectivity seem to have enabled efficiency improvements in production and services, diminishing dependence on more carbon-intensive methods. Comparable dynamics are evident in Moravskoslezsko and the Bratislava region.

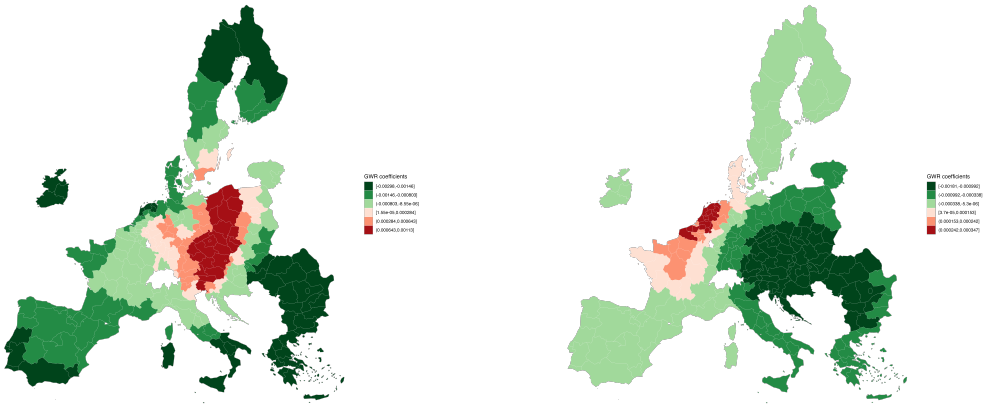
In more sophisticated digital systems, the estimated coefficients approximate zero or may even be positive. Regions like Flevoland and Utrecht, exhibiting upload rates above 45 Mbps in 2019, exemplify this saturation effect. Here, further improvements in quality do not translate into additional environmental benefits; instead, the expansion of data-intensive services, cloud computing, and other high-bandwidth applications may increase energy demand, offsetting efficiency gains. However, not all areas with better connections show the same results. Bucharest-Ilfov, Nord-Vest, and Budapest exceeded 40 Mbps in 2019 but continue to have negative coefficients. This contrast indicates that digital infrastructure by itself does not dictate environmental performance; rather, the results are contingent upon its interplay with regional factors, including the energy mix, industrial base, and the degree of integration of digital technology inside production systems.

Some regions exhibit divergent results for the two digitalisation variables, indicating that they can influence emissions growth through distinct and occasionally contradictory ways. In Berlin, for example, *InternetAccess* correlates with increased emissions growth, although *ConnectionQuality* seems to alleviate it. In Jihozápad, access corresponds with reduced emissions growth, although connection

quality exhibits little decarbonising impact. These examples emphasise that *InternetAccess* frequently reflects behavioural shifts, but *ConnectionQuality* is more closely associated with structural changes in production and services. Depending on the regional context, the two characteristics may function as substitutes or complements rather than progressing together.

In addition to these cross-dimensional dynamics, heterogeneity also arises within countries. In Belgium, Brussels exhibits a negative coefficient for *InternetAccess*, but Limburg demonstrates a positive one. In Germany, faster connections diminish emissions growth in Berlin, although appear to exacerbate it in Schleswig-Holstein. These comparisons demonstrate that, despite a unified national policy framework, regional characteristics determine the impact of digitalisation on environmental results. This highlights the limitations of national evaluations and the significance of regionally disaggregated methods in assessing the sustainability impacts of digital investment.

Figure 4.6: GWR parameters for the *linear specification*.



(a) *InternetAccess* GWR parameters. **(b)** *ConnectionQuality* GWR parameters.

Table 4.8 presents the GWR results derived from the quadratic specification. In comparison to the global model, the incorporation of local factors enhances explanatory power ($R^2 = 0.466$), and the F-tests validate the significance of spatial heterogeneity. The linear and quadratic components of *InternetAccess* exhibit considerable variation between locations, indicating geographically distinct non-

linearities. *ConnectionQuality* is more geographically constant; yet, the consistently positive squared term suggests diminishing returns as speeds increase.

Table 4.8: Summary of GWR coefficient estimates for the *quadratic specification*.

	Min.	**1st Qu.**	**Median**	**3rd Qu.**	**Max.**	**F3 test**
Intercept	-7.2013	-3.2900	-0.38266	1.8171	3.0616	+++
InternetAccess	-0.07978	-0.04734	-0.00023	0.05976	0.1395	+++
$InternetAccess^2$	-0.00076	-0.00033	-0.00000	0.00027	0.00050	+++
ConnectionQuality	-0.00640	-0.00403	-0.00281	-0.00188	-0.00090	
$ConnectionQuality^2$	0.00001	0.00002	0.00003	0.00004	0.00010	
log(Transport)	-0.07190	-0.03395	-0.01879	-0.00552	-0.00140	+++
EnergyIntensiveGVA	0.00292	0.02805	0.08609	0.17468	0.37940	+++
log(Population)	0.01570	0.02669	0.04461	0.06488	0.10930	+++
GDP_pc	-3.1943	-2.7532	-2.3690	-1.8428	-0.9776	+
HDD	0.00001	0.00001	0.00002	0.00003	0.00000	
ProdInnovation	-0.10848	-0.08086	-0.06107	-0.04977	-0.01990	
$log(CO_2)$	-0.06073	-0.01516	-0.00124	0.00661	0.01660	+++
R^2 *OLS*	0.29256					
R^2 *GWR*	0.46574					
F1 test	0.87047+					
F2 test	1.8487					
F4 test	0.75521++					

+++ $p < 0.01$, ++ $p < 0.05$, + $p < 0.1$ (indicates global significance or significant spatial variability).

Figure 4.7 displays the spatial distribution of the local coefficients derived from the quadratic GWR model. Figure 4.7a shows the regional distribution of the estimated coefficients for *InternetAccess*. Strongly negative results are evident in regions of Eastern and Southern Europe, specifically Romania, Bulgaria, Greece, and Hungary, where coverage in 2019 was relatively low. In many regions, improved access corresponds with a deceleration in emissions growth, likely indicating the replacement of more carbon-intensive activities with digital alternatives. Conversely, positive coefficients are observed in developed Western regions, particularly in the Netherlands, where coverage exceeds 95%. In this context, more access is associated with increasing emissions growth, a pattern that aligns with dynamic economies where innovation and production intensity may exacerbate environmental concerns

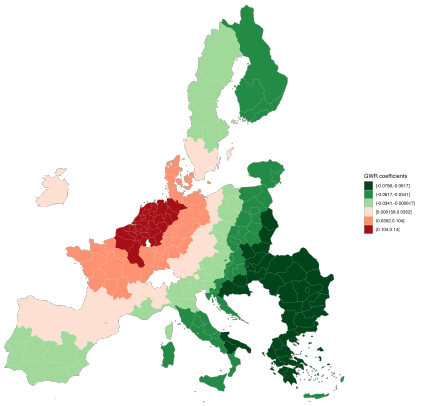
instead of mitigating them.

Figure 4.7b illustrates the estimates for the quadratic term of *InternetAccess*, affirming the existence of non-linearities. In areas with a negative linear effect, notably in Eastern and Southern Europe, the quadratic component is positive, indicating diminishing returns: initial benefits from increased connection drop as coverage approaches saturation. In numerous regions of the Netherlands and Belgium, the positive linear effects are offset by negative quadratic terms, indicating that as access approaches universality, the correlation with emissions growth diminishes. Only a few Southern regions exhibit both negative linear and quadratic impacts, indicating a consistently mitigating link, whereas others display positive coefficients for both components.

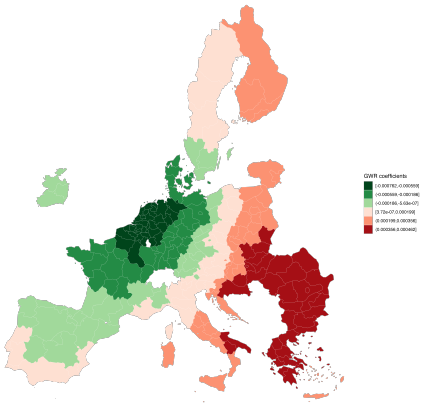
Figure 4.7c shows the local estimated parameters for *ConnectionQuality*. The magnitude of this effect varies significantly. The most substantial reductions (coefficients below -0.006) are observed in Polish regions, where initial speeds in 2019 were low and the economic base is dominated by energy-intensive industries. In these circumstances, enhanced connection quality likely increases efficiency in manufacturing and logistics, promoting decarbonisation. Strong negative effects are also found in Eastern Germany, particularly in Brandenburg and Berlin, where moderate speeds, sophisticated ICT integration, and low-carbon infrastructures indicate that digital quality may serve as a catalyst for systemic transformation. In several regions of Southern and Eastern Europe, the coefficients remain negative yet near zero, suggesting structural barriers or a slower pace of digital adoption in core economic activities.

Figure 4.7d displays the coefficients for the quadratic term of *ConnectionQuality*. The largest positive values are centred in areas where the linear impacts are most negative. This pattern confirms diminishing returns for this variable: initial enhancements in connection quality facilitate decarbonisation, but the advantages decline as digital intensity rises and energy demand increases. In some regions, particularly in South-Eastern Europe, quadratic terms approach zero, aligning with the diminished linear effects and indicating that digital infrastructure has not yet been effectively integrated into industrial processes.

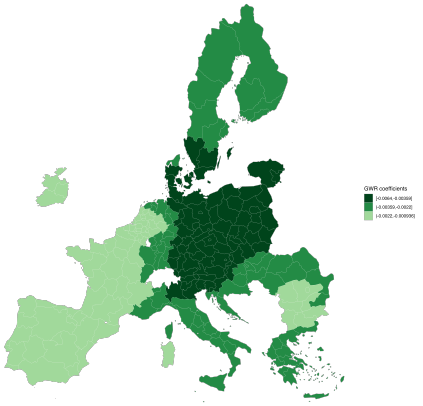
Figure 4.7: GWR parameters for the *quadratic specification*.



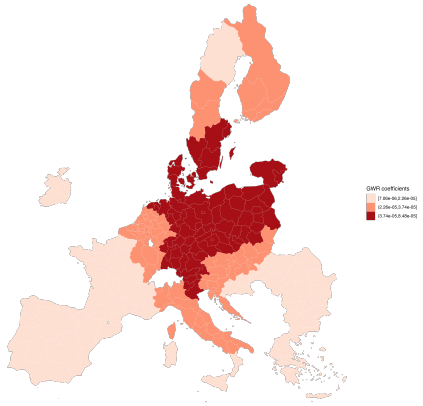
(a) *InternetAccess* GWR parameters.



(b) *InternetAccess*^{2} GWR parameters.



(c) *ConnectionQuality* GWR parameters.



(d) *ConnectionQuality*^{2} GWR parameters.

The results of the third specification, which includes an interaction between *ConnectionQuality* and *InternetAccess*, are reported in Table 4.9. F-tests again support the presence of spatial heterogeneity in the relationship between emissions growth and the selected covariates.

Table 4.9: Summary of GWR coefficient estimates for the *interaction specification*.

	Min.	**1st Qu.**	**Median**	**3rd Qu.**	**Max.**	**F3 test**
Intercept	-1.25690	-0.64662	-0.33863	-0.16836	-0.02120	+++
InternetDummy	-0.01845	-0.00203	0.01537	0.02681	0.09670	
ConnectionQuality	-0.00261	-0.00174	-0.00140	-0.00067	0.00140	+++
InternetDummy ConnectionQuality*	-0.00125	0.00024	0.00079	0.00113	0.00180	
log(Transport)	-0.11087	-0.04274	-0.02347	-0.00657	-0.00010	+++
EnergyIntensiveGVA	-0.13828	-0.09187	-0.07729	-0.05825	-0.01050	
log(Population)	0.01507	0.04383	0.11844	0.20399	0.45760	+++
GDP_pc	0.01098	0.02464	0.04270	0.07242	0.15030	
HDD	-4.1892	-3.3372	-2.8782	-2.1686	-1.3311	+++
ProdInnovation	-4.3123e-06	5.0828e-06	1.6661e-05	3.2804e-05	0.00010	
log(CO_2)	-0.06625	-0.01862	-0.00381	0.00816	0.02010	+++
R^2 *OLS*	0.27274					
R^2 *GWR*	0.45757					
F1 test	0.85896++					
F2 test	1.9302					
F4 test	0.74587++					

+++ $p < 0.01$, ++ $p < 0.05$, + $p < 0.1$ (indicates global significance or significant spatial variability).

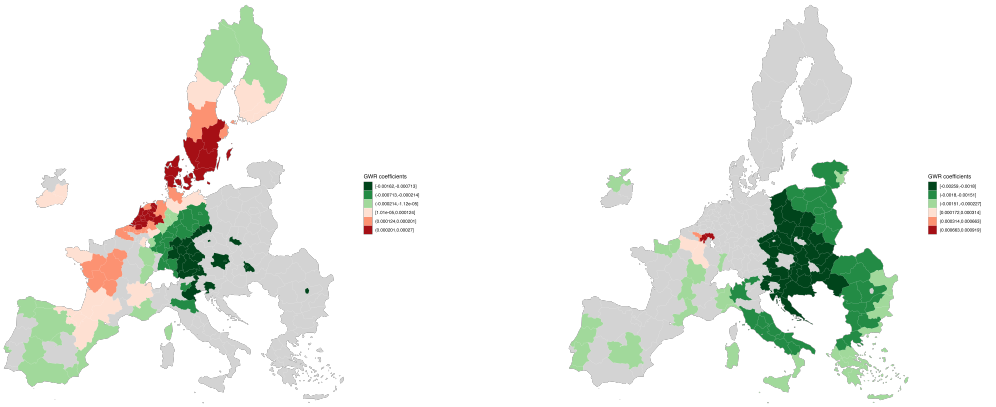
Figure 4.8a illustrates the marginal effect of *ConnectionQuality* in areas with above-average *InternetAccess*, computed as the sum of the main coefficient and its interaction term. The results are markedly heterogeneous: several regions show positive marginal effects, while many display negative impacts. This suggests that in technologically advanced regions, the environmental consequences of quicker connections are not uniform but depend on local circumstances. In areas like Utrecht and Småland med öarna, the marginal effects are approximately zero or slightly positive. Both recorded average upload speeds over 40 Mbps in 2019 and had a relatively small share of energy-intensive sectors in value added. Improvements in connection quality may facilitate energy-intensive activities – such as cloud-based production, complex logistics, or high-frequency data operations – so that efficiency gains are counterbalanced by increased consumption. Conversely, other well-connected regions exhibit significantly negative marginal effects, such as Budapest, Lower Austria, and Detmold. Here, advanced digital infrastructure

integrates with structural characteristics that enhance decarbonisation: lower exposure to energy-intensive sectors, moderate GDP per capita, and the integration of digital tools into more resource-efficient applications.

Figure 4.8b highlights regions with below-average internet access, where no interaction term applies. In this case, the effect of *ConnectionQuality* is considered alone, without quadratic terms or interactions. The spatial distribution is markedly more uniform: most locations display negative coefficients and only a few present positive values. In less digitised regions, improvements in connection are therefore more consistently linked to declines in emissions growth, potentially due to fundamental efficiency gains, the replacement of high-emission activities, or the implementation of straightforward but effective digital solutions.

Taken together, the two panels underscore the importance of geographical heterogeneity and interaction effects. In low-access places, improved connectivity generally facilitates decarbonisation in a consistent manner. In high-access locations, the link becomes more complex, as local economic structures, digital maturity, and industrial mix shape the environmental consequences of digital enhancements. These findings caution against viewing digitalisation as a universal environmental solution and instead emphasise the need for context-specific measures adapted to regional circumstances.

Figure 4.8: GWR coefficients for *ConnectionQuality* under the *interaction specification*.



(a) GWR coefficients for above-average *InternetAccess* regions.

(b) GWR coefficients for below-average *InternetAccess* regions.

In panel 4.8a, coefficients are obtained by summing the local effects of *ConnectionQuality* and its interaction term; in panel 4.8b, only the coefficients of *ConnectionQuality* are reported.

4.5 Conclusions and policy implications

This study examined the relationship between digitalisation and environmental dynamics within the European Union, with a specific focus on heterogeneity. Although digital technologies have been increasingly integrated into social and economic institutions, their environmental consequences are context dependent. The disparities in economic development and innovation across EU regions (Giannini and Martini 2024) may affect their capacity to adopt and utilise digital technologies, subsequently influencing the environment. To investigate these dynamics, we analysed 226 EU NUTS 2 regions from 2019 to 2022, assessing how internet availability and connection quality in 2019 affected the growth rate of per capita CO2 emissions. The analysis integrated global, distribution-sensitive, and spatially localised models – specifically OLS, QR, and GWR – to discern both average and heterogeneity effects. By employing these methodologies, we moved beyond standard assumptions of uniform impact and offered a deeper comprehension of

the digital-environment relationship across varied territorial contexts.

The findings highlight two primary dimensions of heterogeneity. The first concerns the positioning of regions within the emissions-growth distribution. Differences among quantiles suggest that the environmental impact of digitalisation is contingent upon the level of decarbonisation already achieved. Regions situated at the centre of the distribution seem to derive the greatest benefits: digitalisation in these areas acts as a catalyst for efficiency improvements, enabling the optimisation of production, logistics, and communication activities. Conversely, the environmental advantages are diminished in areas with already low emissions, due to limited potential for additional reductions, and in high-emission locations, where digitalisation interacts with existing industrial frameworks and fossil fuel-based energy systems. This pattern reveals that digital technologies are most effective when economies are in transition – where carbon reduction potentials and adaptive capacities coexist – while their impact is diminished at the extremes of the environmental spectrum.

The second dimension refers to geography. The spatial variability revealed by GWR highlights how local economic frameworks and energy systems influence the environmental impacts of digitalisation. In less connected or industrially diversified areas, improvements in connectivity and access support behavioural and organisational changes that reduce emissions, for instance through teleworking or the dematerialisation of services. Conversely, in developed or energy-intensive areas, technological advancement may exacerbate energy demand, particularly when data-driven industries, cloud services, and manufacturing depend heavily on carbon-based power sources. These contrasting outcomes demonstrate that digitalisation does not automatically lead to more sustainable trajectories; its environmental impacts are shaped by regional factors and may either exacerbate or mitigate structural inequalities across Europe.

The two forms of heterogeneity – distributional and spatial – demonstrate that the digital-environment nexus cannot be captured by a single, average relationship. Digitalisation interacts with local development paths, institutional frameworks, and energy systems. Where these frameworks facilitate innovation and clean

technology, digitalisation can accelerate decarbonisation. In their absence, the same dynamics risk reinforcing carbon-intensive habits. This calls for a redefinition of digital transitions: not solely as technological advancements, but as context-dependent processes whose environmental impacts depend on underlying economic and infrastructural conditions.

Non-linear and interaction effects further clarify these dynamics. The tendency for digitalisation to generate benefits at early stages and rebound effects at higher levels of maturity suggests that environmental gains depend not only on the diffusion of digital technologies but also on how they are integrated into regional systems. Without complementary measures guiding their use – such as incentives for digital applications that improve energy management or monitoring – digital expansion alone may raise energy demand and offset efficiency gains. The results therefore point to the need for a nuanced understanding of digitalisation as a process whose environmental impact is conditioned by both regional context and level of development.

The results can be interpreted within the framework of the European Union's existing regional policy, which already offers instruments for addressing disparities in territorial development. Cohesion policies, the European Regional Development Fund, and the Just Transition Fund all play a central role in supporting both digital and environmental transitions. The evidence presented here suggests that these tools could be used more strategically to address the differentiated environmental outcomes of digitalisation. The challenge lies in adapting existing instruments to better reflect territorial conditions, rather than introducing new ones. This requires identifying the intersections between digital expansion and decarbonisation, as well as recognising the areas where it may exacerbate energy demand or industrial dependency. In less connected areas, digital investment can improve efficiency and decrease emissions when combined with capacity-building and innovation support. In more advanced regions, policy attention should focus on the environmental management of digital infrastructures themselves – through greener data centres, renewable-powered networks, and stronger monitoring of energy-intensive sectors. This perspective aligns with the EU's commitment to cohesion but underscores that convergence in digital infrastructure does not automatically produce convergence

in environmental outcomes. Addressing this gap requires stronger coordination between digital and climate policies across different governance levels, as well as evaluation frameworks that explicitly include environmental indicators in the assessment of digital policies. Ultimately, what matters is not merely the speed of regional digitalisation, but how it is governed and embedded within the economic and energy structures that determine the sustainability of regional development.

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Chapter 5

Conclusions

This thesis reconsiders the relationship between digitalisation and the environment by reframing it through a territorial lens. While much of the existing literature has approached digitalisation as a homogeneous process producing uniform environmental effects across countries (Haseeb et al. 2019; Chatti 2020; Briglauer et al. 2023), this work demonstrates that its implications are inherently spatial and emerge through the interaction between digitalisation and regional structures of production and development (Crescenzi and Rodríguez-Pose 2011; Capello and Lenzi 2013; McCann 2020). It shows not only that the expansion of digital infrastructure can influence environmental outcomes beyond local boundaries – through interconnections among areas with different levels of digital development – but also that the direction and intensity of these effects vary according to regional characteristics. This spatial differentiation challenges the notion of a single "green" digital transition (EEA 2024). It instead advances a more grounded interpretation of the twin transition, in which spatial dependence and heterogeneity (Anselin 1988; LeSage and Pace 2009) help explain why similar digital transformations yield diverging environmental outcomes across territories. As a result, simplistic classifications of digitalisation as "green" or "brown" become increasingly untenable.

The study pursued three complementary objectives. From a conceptual standpoint, it aimed to clarify the main mechanisms linking digitalisation and the environment, offering a systematic synthesis of heterogeneous empirical findings and highlighting

key gaps in the regional literature. From an empirical standpoint, it examined the digital-environment relationship at two interconnected spatial scales. First, through a national analysis of Italy, it investigated the environmental consequences of the fibre optic roll-out and evaluated whether digitalisation produces local and interregional effects on air quality. Second, it broadened the scope to European regions to assess whether the environmental impact of digitalisation varies across space and along the emissions growth distribution. From a methodological standpoint, the thesis explores the spatial dimension of the digital-environment nexus by combining approaches that capture interregional connections and regional heterogeneity.

Accordingly, the empirical chapters followed a progressive structure. Chapter 2 presented a systematic review of the literature on digitalisation and environmental outcomes, identifying three primary gaps: (i) the direction and magnitude of the digital-environment nexus, (ii) the assumption of linearity in most empirical studies, and (iii) the limited attention to spatial and regional heterogeneity. Chapter 3 addressed these gaps within the Italian context, assessing the environmental impact of the fibre optic deployment and the presence of geographical spillovers among neighbouring areas. Chapter 4 built on these findings by examining the European context, emphasising the variability of the digital-environment link across regions and along the emissions distribution, and investigating the relevance of geographical non-stationarity.

This final chapter summarises how the thesis achieves its objectives, discusses its main empirical and methodological contributions, and reflects on the broader implications for research and policy.

5.1 Insights from the thesis

The literature review provided the conceptual framework for the thesis by analysing how previous studies have examined the relationship between digitalisation and environmental outcomes. The review uncovered a fragmented body of evidence, marked by conflicting results. While some studies indicate that digitalisation

improves energy efficiency and lowers emissions through technological upgrading, process optimisation, and enhanced resource management, others highlight rebound effects and increased energy consumption linked to the expansion of digital infrastructure and data-intensive services. This divergence revealed that the environmental consequences of digitalisation cannot be regarded as intrinsically beneficial or detrimental but are instead contingent on context and shaped by structural, behavioural and spatial factors.

A second important insight concerned the widespread assumption of linearity in the digital-environment relationship. Numerous empirical studies have modelled digitalisation as having a uniform effect on environmental indicators, overlooking potential thresholds, diminishing returns, or non-linear dynamics across stages of digital development. Acknowledging this limitation informed the subsequent decision to adopt approaches capable of capturing variations in both the magnitude and the direction of effects along the emissions distribution.

The review also highlighted the territorial blind spot present in much of the current literature. Most research focuses on national or cross-country datasets, neglecting the spatial interdependencies and complexities that characterise regional systems. Few studies examine how regional innovation capacity, industrial structure, or infrastructural endowments condition the environmental impact of digitalisation. This gap justified the thesis's regional approach and the adoption of econometric methods specifically designed to account for spatial dependence and non-stationarity.

By systematically identifying these gaps, the review informed the empirical design of the thesis in two key respects. First, it underscored the need to analyse the digital-environment nexus across multiple spatial scales: a national case study (Italy) to investigate mechanisms and spillovers in depth, and a European-wide analysis to assess the extent of regional heterogeneity. Second, it guided the methodological decision to combine spatial econometrics, QR, and GWR, thereby going beyond the standard, spatially homogeneous approaches prevalent in existing research.

Building on these, the Italian analysis provided the first empirical application of

the thesis framework and offered an initial opportunity to examine the interplay between digitalisation and environmental dynamics within a specific territorial context. Italy represented an ideal setting for this investigation: the national fibre optic deployment occurred unevenly across regions, reflecting differences in infrastructural development, industrial structure, and institutional capacity.

The findings suggested that the diffusion of fibre optic networks was associated with an improvement in air quality, as evidenced by a decrease in PM10 emissions. This relationship remained robust across different model specifications and was not limited to the provinces where infrastructure expanded. The analysis also demonstrated that environmental benefits extended to neighbouring provinces, providing clear evidence of spatial spillovers. This indicates that the environmental advantages of digitalisation are not confined to specific areas but can spread through interregional connections such as commuting, trade dynamics, and shared production systems. Improvements in digital connectivity in one region may indirectly enhance environmental performance in others, thereby amplifying the overall impact beyond local administrative boundaries.

In addition, part of the relationship operates through changes in mobility patterns, consistent with a process of behavioural adaptation. Enhanced digital connectivity facilitates remote work, online service delivery, and digital communication, thereby reducing the need for physical travel. Hence, the environmental benefits associated with fibre expansion arise not only from technological efficiency but also from a reconfiguration of economic and social interactions.

The Italian findings clearly demonstrated that digitalisation can enhance environmental performance through both technological and behavioural mechanisms, while also highlighting the need to account for spatial dependence when assessing its effects. This case provided a concrete illustration of how digital infrastructure and environmental outcomes interact within a territorially interconnected system, establishing both empirical and conceptual foundations for extending the analysis to the European regional scale.

At the European scale, the analysis examined the growth of carbon emissions, investigating not simply whether digitalisation is “beneficial” or “harmful”, but how

it influences the rate of environmental change across different regional contexts. Digitalisation was observed through two complementary lenses. One captures access – the breadth of connectivity and the extent to which households are online. The other reflects quality – the speed and reliability that enable more intensive, dematerialised activities, ranging from cloud services to remote collaboration. These dimensions represent different stages of the process: access concerns diffusion, while quality relates to what becomes possible once diffusion is established.

Viewed through this dual lens, the evidence points in a clear direction. Digitalisation is associated with slower emissions growth, particularly during the early stages of the transition. When regions move from limited connectivity to a more robust digital maturity, the environmental benefits appear first, before diminishing returns emerge. The initial steps – enabling substitution, coordination, and basic efficiency – are crucial; subsequent improvements become subtler and more dependent on context.

The distributional perspective reinforces this interpretation. Examining the entire spectrum of emissions growth – through the QR – shows that digitalisation acts less as a lever that changes outcomes everywhere and more as a stabilising force where trajectories remain flexible. In the middle of the distribution, where emissions are neither falling nor accelerating, improvements in access and, especially, in connection quality correspond to slower emissions growth. In these contexts, digital tools can reorganise production, logistics, and everyday routines. At the extremes, however, the relationship weakens: where emissions are already under control, efficiency margins have largely been exhausted; where they are rising rapidly, structural forces prevail and digitalisation alone cannot reverse the trend.

The spatial perspective adds further depth. The GWR analysis did not draw clear boundaries across Europe but instead revealed a pattern of local regimes, where the association between digitalisation and emissions growth varies in intensity and sometimes even changes direction over short distances. Two insights stand out. First, variation within countries is often as significant as differences between them: neighbouring regions may sit at very different stages of the digital transition and thus translate connectivity into environmental outcomes in distinct ways.

Second, spatial context interacts with digital development: in some areas, the environmental signal is driven mainly by quality, where advanced digital uses are already established; in others, access remains more relevant, marking the threshold where basic connectivity begins to influence change. Between these two extremes lie transitional zones, where organisational adaptation has begun but not yet reached critical mass.

Taken together, these findings provide a more grounded understanding of the digital-environment relationship. Digitalisation tends to moderate the growth of emissions by improving coordination, enabling remote interaction, and promoting more efficient production – yet only where regional conditions are prepared to absorb these shifts. Rather than producing a uniform environmental effect, digitalisation generates different regional pathways, as similar technologies lead to different outcomes depending on each region's position in the transition and its capacity to translate connectivity into lower-carbon practices.

5.2 Policy relevance

The findings of the thesis have implications not for the formulation of new policies, but rather for the interpretation, coordination, and evaluation of existing ones. Digitalisation and environmental strategies already coexist across several levels of governance – European, national, and regional. However, their interaction often produces uneven outcomes, and the results of this research help to clarify the reasons behind this pattern. Across both the Italian and European analyses, the environmental effects of digitalisation proved highly context-dependent. The same policy intervention can therefore produce contrasting results across regions. Recognising this diversity calls for strengthening the multi-level governance that connects these scales, rather than designing new measures for each. This means aligning digital and environmental initiatives, clarifying shared objectives, and acknowledging that progress will manifest differently across territorial contexts.

The Italian evidence also highlighted the presence of spillover effects, showing that the benefits of digitalisation can extend beyond administrative boundaries. This

finding underscores that local initiatives should not be viewed in isolation, as the digital transition operates within functional and interconnected spaces. Better coordination – both across regions and across sectors – can amplify these positive externalities and prevent them from dissipating at jurisdictional borders. Yet, persistent territorial differences in institutional quality (Nifo and Vecchione 2015) may hinder this diffusion, as regions with weaker institutions are less able to absorb and sustain the benefits of digitalisation.

This perspective emphasises the importance of policy cooperation over differentiation. Horizontal measures – such as broadband investment, innovation incentives, or digital skills programmes – remain essential, yet their effectiveness depends on how they interact with local conditions and with the regional policies that accompany them. Stronger coordination among these layers can help ensure that the environmental potential of digitalisation is realised more evenly, preventing the twin transitions from widening existing territorial disparities.

5.3 Bridging the twin transition: spatial lessons and future directions

This thesis approached digitalisation and the environment not as separate domains, but as two dimensions of the same structural transformation. This choice reflected the European policy context, in which the digital and green transitions are increasingly promoted as interdependent pillars of sustainable development. However, although they are often addressed jointly in strategic agendas, their interaction – and the geographical disparities that shape it – remains only partially understood. The study therefore aimed to investigate this relationship empirically, analysing how the two processes evolve across Europe's diverse regional landscape.

The findings and reflections presented in this thesis provide a contribution to understanding how technological and environmental change intersect across space. In particular, the analysis offered empirical evidence that helps explain why the environmental impacts of digitalisation differ between regions. By integrating the

digital and environmental transitions within a territorial framework, it demonstrated that spatial diversity is not a secondary factor to be managed, but a fundamental element of how these processes take shape throughout Europe.

Looking ahead, this perspective opens several avenues for future research. Extending the temporal dimension of the analysis could clarify how digitalisation interacts with longer-term environmental transitions, while incorporating sectoral and micro-level data may reveal the mechanisms through which efficiency improvements, behavioural change, and policy interventions combine over time. The spatial perspective can also strengthen the link between academic research and policy evaluation by revealing how regional trajectories of digital and green transitions unfold in clustered and uneven ways across Europe (Fazio et al. 2025), thereby clarifying not only whether progress occurs, but where and why it takes form.

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