Critical Infrastructures and Their Role in Regional Resilience: Mapping EU Regions

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Abstract
This study assesses the spatial distribution of critical infrastructure and its implications for regional resilience across EU NUTS-2 regions. The study develops a composite indicator for critical infrastructure stock using data on transport, energy, ICT, and public services, capturing both demographic and geographical accessibility. Findings reveal strong spatial disparities, with Central and Northern regions generally better equipped than Southern and Eastern counterparts. A median-split based typology to assess the sufficiency of CI Stock classifies regions into four categories, highlighting that only 9% exhibit high sufficiency across all sectors. Many regions show imbalanced critical infrastructure stock profiles, underscoring the need for multi-dimensional assessment. The study offers a quantitative framework for identifying vulnerabilities and guiding regional policies, stressing the importance of sufficient critical infrastructure, spatial equity, and integrated regional planning in strengthening regional adaptive capacity.

Keywords: Regional resilience; critical infrastructure stock; disaster prevention

1. Introduction

Regions are becoming increasingly interconnected through population mobility, economic flows, and infrastructure systems, forming complex webs of interdependencies that shape both their development trajectories and resilience. As these interregional linkages deepen, the capacity of regions to withstand and recover from disruptive events has emerged as a core concern for planners and policymakers. Within this context, critical infrastructures (CIs) including transport systems, electricity grids, digital networks, and water supply, play an essential role in maintaining societal and economic functioning. These infrastructures not only support the everyday routines of regional life but also underpin the capacity to absorb shocks and ensure continuity during times of disruption. However, their interconnectedness means that the failure of one component may trigger cascading effects across regions, exacerbating crises and magnifying risks (Shi et al., 2021).

Resilience, broadly understood as a system's ability to adapt to change and recover from disturbances (Boschma, 2015), is thus intimately linked to the structure, sufficiency, and interdependency of CIs in the regions. Inadequate backups, spatial inequalities, or an overdependence on single infrastructure hubs can transform localized hazards into systemic breakdowns. Studies highlight that resilience involves networks of linked adaptive capacities, making connectivity crucial as it provides alternative paths during disruptions (Reggiani et al., 2015). However, Reggiani (2022) highlights a key trade-off: highly connected hubs enhance efficiency but risk severe cascading failures when disrupted, whereas decentralized and redundant networks, although less efficient, enhance resilience. Redundancy, originating from ecological studies, refers to having multiple alternatives ensuring continued system function despite disruptions (Galland et al., 2020). For critical infrastructure, redundancy mitigates risks by providing alternative pathways, thus minimizing cascading effects from failures (Bauer et al., 2012; Sheffi, 2005; Akbarzadeh et al., 2017; Forcellini, 2023).

The conceptualisation of what is deemed "critical" infrastructure is not fixed. It is shaped by policy frameworks, academic interpretations, and societal needs. While energy, transport, and ICT are frequently emphasized in both academic and policy discourse, sectors such as education, housing, and healthcare, though vital, are often overlooked (Huddleston et al., 2022; DGAP, 2023). This reflects underlying epistemological and political commitments that determine which systems are prioritised for protection and investment.

This paper aims to address these complexities by mapping the stock of critical infrastructures across EU NUTS-2 regions and exploring their relationship with regional resilience. Instead of focusing on distinct infrastructure failures or individual case studies, we adopt a regional approach. We construct composite indicator of critical infrastructure stock based on availability, sufficiency, and distribution, and assess how these patterns vary across the EU.

By visualising the geography of CI stock and their potential insufficiencies, the study seeks to bridge the gap between theoretical studies and practical planning tools for resilience. Ultimately, this work contributes to emerging debates on how infrastructure systems can support regions in facing future uncertainties through enhancing robustness, improving recovery capacities, or enabling equitable access to essential services.

2. Conceptual Framework

2.1. Critical Infrastructure

Understanding the role of critical infrastructure in shaping regional resilience requires a careful conceptualisation of what these systems are, how they function, and why their presence or absence matters. Critical infrastructures are not just physical networks but systems that enable the delivery of essential services, support social and economic functioning, and influence a region's capacity to respond to disruptions (Deelstra and Bristow, 2023). Their criticality becomes most visible during crises (Steele et al., 2017), when breakdowns in infrastructure; such as electricity failures, blocked transport routes, or collapsed communication networks, can escalate the impacts of hazards and delay recovery (Thévenaz and Resodihardjo, 2010; Ke and Hsu, 2022).

There is no universally accepted definition of critical infrastructure. The term is used across academic disciplines and policy frameworks with varying scopes and emphases. In general, what distinguishes critical infrastructure from "basic" infrastructure is the severity of consequences associated with its disruption. As Burgess (2007) and Gallais and Filiol (2017) argue, infrastructure becomes "critical" when its failure transforms a disturbance into a broader crisis, threatening public safety, economic continuity, and the delivery of core services. The concept of criticality, in this sense, is relational and contingent on both societal needs and political priorities.

Larkin (2013) offers a foundational understanding of infrastructure as systems that enable the operation of other systems. He emphasises that infrastructures are not just technical objects but also social and relational structures. In the case of critical infrastructure, this means recognising the ways in which roads, hospitals, and power grids connect people, places, and institutions; not just materially, but functionally and politically. Infrastructures are embedded in everyday life and often remain invisible until they fail.

Policy definitions of critical infrastructure have evolved in response to changing threat perceptions and disruptive events. The United States was among the first to define and institutionalise the concept in the 1990s, particularly after the Oklahoma City bombing and later, following September 11 attacks, broadened its conception of CI (Moteff, 2007; Zebrowski and Sage, 2017; Collier and Lakoff, 2008). Since then, the list of sectors designated as critical has expanded significantly, including domains such as finance, emergency services, and digital infrastructure (Cybersecurity and Infrastructure Security Agency, 2025). While the U.S. provided one of the earliest formal definitions of critical infrastructure, policies on critical infrastructure in the EU date back to 2004, following key disruptive events such as the 2003 Italian blackout and the 2004 Madrid train bombings. These events prompted the launch of a strategic framework for critical infrastructure protection, which led to the establishment of the European Programme for Critical Infrastructure Protection (EPCIP) and the adoption of Directive 114/2008 aimed at strengthening infrastructure security which focused on transport and energy. However, the more recent CER Directive (2022/2557) reflects a broader view. It includes eleven sectors, such as public administration, healthcare, and the food supply chain, and introduces a shift from protection to resilience (Božović, 2023). The Directive on the Resilience of Critical Entities, effective from 16 January 2023, requires EU Member States to implement national legislation by 17 October 2024. It addresses eleven sectors: energy, transport, banking, financial market infrastructure, healthcare, drinking water, wastewater, digital infrastructure, public administration, space, and food supply chains (European Commission, 2024). While each member state identifies and protects national critical infrastructures, the EU also promotes cooperative measures for transnational coordination.

Beyond the US and EU, modern definitions of critical infrastructure in various countries are largely similar in scope, most nations include infrastructure for energy, transportation, communications etc. as "critical". A 2023 study by the German Council on Foreign Relations (DGAP) analysing how 100 countries define and perceive critical infrastructure (CI) sectors is illustrating this well. According to the study, the most frequently cited sectors are energy, ICT, and transport, respectively, whereas sectors such as water, food, national security, and research & education are mentioned far less often.

What often differs is priority and emphasis, each state may prioritize certain sectors over others based on its unique needs and risk perceptions, which have the potential to obscure the distinction between infrastructure critical for basic societal survival and that which is deemed critical primarily for a nation state's interests (Newbill, 2019). Moreover, given that most CI systems are owned and operated by private entities, the influence of market and neoliberal governance cannot be overlooked (de Bruijne and van Eeten, 2007). Therefore, it is important to prioritize society's fundamental needs by focusing on a core set of universally critical infrastructures, which extend beyond national boundaries and can be narrower than those broadly defined by state interests (Newbill, 2019). As academic studies have highlighted, infrastructures that are not prioritised in formal frameworks such as housing, education, or childcare may still be essential for maintaining well-being and everyday functioning (Huddleston et al., 2022). The scope of what is considered critical thus reflects political, economic, and epistemological decisions, often influenced by prevailing governance models and private sector interests.

2.2. Regional Resilience and Critical Infrastructure

Resilience, while a debated and multidimensional concept, is broadly understood as the ability of socio-economic systems to adapt to both internal and external changes. Martin and Sunley (2015) conceptualise regional economic resilience as a process comprising four dimensions: vulnerability, resistance, robustness, and recoverability. Vulnerability reflects the extent of exposure to shocks, while resistance denotes a system's capacity to withstand them. Robustness refers to the ability to maintain core functions under stress, and recoverability measures how quickly and effectively a system returns to its prior trajectory. Other scholars, such as Sun et al. (2018), further highlight the role of redundancy and fast recovery mechanisms in building resilience.

Critical infrastructure plays a central role in supporting resilience by enabling continuity in essential services such as energy, transport, and healthcare. Although many studies focus on single sectors such as electricity (Afgan & Veziroglu, 2011), water (Sitzenfrei, 2011; Hwang, 2013), or digital networks (Boh et al, 2023), these analyses consistently demonstrate that infrastructure sufficiency enhances both robustness and recoverability. Some studies note that resilience is not only about infrastructure robustness but also about resourcefulness, and coordination between systems (Hickford et al., 2015). Other studies providing frameworks like the Resilience Measurement Index (Carlson et al., 2012) and spatial vulnerability models (Demirel et al., 2015) aim to quantify infrastructure resilience; yet, a gap remains in cross-sectoral evaluations for wider geographies.

Despite its conceptual richness, the empirical assessment of critical infrastructure (CI) and its contribution to regional resilience remains rather unexplored. Since, critical infrastructure is difficult to measure uniformly across regions, many studies focus on single sectors or isolated case studies which are limiting comparability and generalisability. While monetary values such as investment amounts are commonly used, scholars argue that physical indicators (like kilometres of roads or electricity capacity) provide more meaningful and comparable metrics across regions (Canning, 1998; Bröcker, 2009). However, these are not neutral; they are shaped by geography, urbanisation, and income levels. Data limitations, including the private ownership of many CI systems and security restrictions, further complicate standardised measurement.

A key methodological issue is endogeneity, whether critical infrastructure stock creates resilient regions or resilient regions attract infrastructure. Studies that are focusing on the relationship between regional development and infrastructure attempt to address this challenge using historical infrastructure paths, planned routes, or inconsequential units approaches (natural experiments) (Redding & Turner, 2014), yet establishing causality remains difficult. Moreover, infrastructure often produces spatial spillovers, benefiting areas beyond their immediate location, and these functional interdependencies are rarely captured in standard models. Although methods like fault tree analysis, input-output models, agent-based simulations, and network modelling are increasingly applied (Chopra and Khanna, 2015; Pant et al., 2015), more comprehensive spatial assessments remain limited.

Building on this literature, this study approaches critical infrastructure as a system of interdependent networks that deliver essential services. Rather than focusing on disruptions or hazard events, the emphasis is placed on infrastructure sufficiency and spatial distribution, what we define as critical infrastructure stock. To this end, we develop a composite indicator for critical infrastructure stock at the NUTS-2 level for EU regions, where data availability and institutional coherence support meaningful cross-regional comparison.

3. Data and Methodology
3.1. Data
Data for this study were collected from a range of publicly available sources, with an emphasis on spatial precision and coverage. Most indicators were collected in georeferenced format and processed using QGIS software to enable spatial analysis and aggregation at the regional level.

- **Transport**: Road and railway networks, stations, and airports were obtained from EuroGlobalMap (2025) and Eurostat GISCO (2013).
- **Energy**: Power plant data (capacity and number) were sourced from the Global Energy Monitor (2024) and OpenStreetMap (2025) for infrastructure components such as powerlines and towers.
- **ICT**: Internet access data were retrieved from Eurostat (2024), expressed as the share of households with internet connection.
- **Public Services**: The number of hospitals and educational facilities was derived from OpenStreetMap (2025), and the surface area dedicated to sports and leisure activities was obtained from the CORINE Land Cover dataset (2018).

Table 1. Data Variables and Sources

CI Sectors	CI Stock Variables	Source	Year
Transport	1. Roads (line) 2. Railways (line) 3. Railway stations (node) 4. Airports (node)	1. EuroGlobalMap 2. EuroGlobalMap 3. EuroGlobalMap 4. Eurostat GISCO Airports 2013 dataset	1. 2025 2. 2025 3. 2025 4. 2013
Energy	1. Power plants (node) 2. Tower/mast (node) 3. Power lines (line)	1. Global Energy Monitor 2. OpenStreetMap 3. OpenStreetMap	1. 2024 2. 2025 3. 2025
ICT	1. Households that have access to internet (%)	1. Eurostat	1. 2024
Public Services	1. Health facilities (node) 2. Schools (node) 3. Sports/leisure activities (polygon)	1. OpenStreetMap 2. OpenStreetMap 3. CORINE Land Cover	1. 2025 2. 2025 3. 2018

The dataset covers 234 NUTS-2 regions. Due to the limitations in data availability and concerns of consistency, some regions that are predominantly islands or overseas territories were excluded from the analysis. These include Ciudad Autónoma de Ceuta and Ciudad Autónoma de Melilla in Spain; Canarias; the autonomous Portuguese regions of Açores and Madeira; and the French overseas territories of Guadeloupe, Martinique, Guyane, La Réunion and Mayotte.

3.2. Methodology

To comprehensively evaluate regional patterns in critical infrastructure (CI) stock, we employed a dual-method approach. The first method involved constructing a composite indicator that synthesizes sectoral CI stock scores (standardized by both population and land area) into a single metric, thereby enabling cross-regional comparison of overall infrastructure levels. The second method builds upon these composite scores by distinguishing between spatial coverage and infrastructure sufficiency relative to population. Through a typology-based classification using median splits, we assigned regions to distinct categories reflecting combinations of high or low spatial and demographic provision within each CI sector. This approach not only reveals underlying patterns of CI distribution but also addresses the key research question: Are there regions that perform strongly or weakly across all dimensions, or do certain regions exhibit mixed infrastructure profiles? For example, a region classified as high per capita and high per land area in transport can be considered both well-connected and accessible, while a region with low per capita but high per land area may possess extensive infrastructure coverage yet still lack adequate provision relative to its population, which an important distinction for assessing resilience. Similarly, in the energy sector, high numerosity but low capacity indicates redundancy but potential underpowering, whereas low numerosity with high capacity suggests robustness but limited redundancy. By integrating these two methods, our analysis aims to provides a more nuanced understanding of infrastructure sufficiency and distribution across regions.

3.2.1. Composite Indicator Construction

In the literature, studies developing datasets covering both geographical and sectoral breadth to enable comparisons across multiple regions and countries are limited. A similar motivation guided Canning (1998) in developing a worldwide infrastructure database. In his study, Canning examines infrastructure stock through physical indicators expressed per land area and per capita. He justifies the use of these physical indicators by highlighting that countries can vary significantly in infrastructure's per-unit costs due to differences in input prices and variations in public sector efficiency. Bröcker (2009) further adds that natural conditions, which may vary not only among but also within countries, can significantly affect infrastructure costs due to natural conditions for example. He provides examples of physical indicators useful for assessing infrastructure stock, such as road and railway length (km) and electricity supply capacity (megawatts).

A more recent study by Nirandjan et al. (2022) provides a global dataset of critical infrastructure (CI) derived from detailed OpenStreetMap (OSM) data, covering seven sectors: transport, energy, telecommunications, water, waste, education, and health. Similar to their Critical Infrastructure Spatial Index (CISI), which aggregates multiple standardized critical infrastructure indicators into composite spatial scores at varying resolutions to reveal hotspots of CI concentration at global scale, our approach involves combining infrastructure metrics standardized per capita and per land area through min-max normalization. In our study, these normalized indicators were further aggregated into a single composite indicator at regional scale, ensuring both demographic accessibility and geographic coverage are comprehensively reflected.

Based on these takeaways from the literature; in order to assess the availability and sufficiency of infrastructure, two standardised measures were calculated for each variable: per capita and per land area. These indicators were first computed individually, then normalised using min-max scaling. The two dimensions were averaged to capture both demographic reach and spatial coverage. For each sector, the standardised indicators were then summed and re-normalised to ensure comparability across regions.

In the case of energy infrastructure, the number of power plants (numerosity) and total installed capacity were evaluated separately by both population and land area. This distinction acknowledges that while large-capacity plants may enhance robustness, they can also introduce vulnerability due to over-reliance on a limited number of high-output facilities. A system dominated by a few large sources may lack the redundancy needed for resilience during disruptions.

For ICT, which consists of a single variable (the share of households with internet access), the indicator was directly standardised. Finally, the four sectoral scores transport, energy, ICT, and public services were combined with equal weights into a single composite index of critical infrastructure stock.

1. Density Calculation: For each indicator (e.g., kilometres of roads and railways, number of hospitals), we calculated values per capita and per square kilometre at the NUTS-2 level.

2. Min-Max Normalisation: Each per capita and per land value was normalised using min-max scaling:

$$x_{capita}^{norm} = \frac{x_{capita} - \min(x_{capita})}{\max(x_{capita}) - \min(x_{capita})}$$

$$x_{land}^{norm} = \frac{x_{land} - \min(x_{land})}{\max(x_{land}) - \min(x_{land})}$$

3. Averaging Spatial and Demographic Dimensions: The two standardised values (per capita and per land) were averaged to reflect both demographic accessibility and spatial coverage.

$$x_{avg} = \frac{x_{capita}^{norm} + x_{land}^{norm}}{2}$$

$$x_{avg}^{norm} = \frac{x_{avg} - \min(x_{avg})}{\max(x_{avg}) - \min(x_{avg})}$$

4. Re-normalisation: These average scores were standardised again to preserve comparability across indicators within the same sector.

5. Sectoral Aggregation: For transport, energy, and public services, the re-normalised values of each indicator were summed and standardised once more to produce a final **sectoral infrastructure score**. ICT, which includes only a single indicator, was directly standardised.

6. Composite CI Score: The four sectoral scores were then summed-up, assigning equal weight to each, and then standardised to form a **total critical infrastructure score** for each region

$$Total\ Score = Transport^{norm} + Energy^{norm} + ICT^{norm} + Public\ Services^{norm}$$

$$Normalized\ Total\ Score = \frac{CI - \min(CI)}{\max(CI) - \min(CI)}$$

3.2.2. CI Stock Classification and Median-Split Approach

As a second step, to interpret regional differences in critical infrastructure stock and identify broader patterns, we implemented a typology-based classification approach. This method aligns with other studies in the literature aiming to spatially classify infrastructure stocks using typological or cluster-based methods (Borgatti, 2008; Onda et al., 2014: Nirandjan et al. 2022).

Instead of relying on unsupervised, data-driven algorithms (such as hierarchical clustering or k-means), which are typically favoured for very large datasets (Xu et al., 2017), we opted to categorize continuous CI scores using a median-split approach. This technique, adopted in previous studies (e.g., Trojanowski et al., 2024; King et al., 2011), facilitates targeted comparison of infrastructure provision patterns across regions and sectors, supporting both spatial and cross-sectoral assessments. While some critiques exist regarding the potential for median splits to reduce statistical power and obscure underlying variation (DeCoster et al., 2011), this method enhances interpretability and is particularly valuable where clear typological distinctions are required and multicollinearity is limited (Iacobucci et al., 2015). Based on the idea that a manual median-split approach ensures results are transparent, directly comparable, and easy to interpret making it particularly suited for policy-oriented assessments we applied median splits to categorize continuous variables for typology construction.

For each sector, we assessed regional infrastructure typologies using median splits of standardized indicators, considering combinations of per capita and per land measures or numerosity and capacity for energy (excluding powerlines and towers). Specifically, for Transport, Energy, and Public Services, regions were categorized into four typological groups (High-High, High-Low, Low-High, and Low-Low) based on these dual axes. For ICT, which relied on a single indicator (household internet access), a simple High vs. Low classification relative to the median was applied.

Subsequently, each region was assigned a score based on its typological classification within each sector: two points were allocated for the highest-performing typologies (e.g., High-High combinations), one point for intermediate typologies (High-Low or Low-High), and zero points for the least sufficient typologies (Low-Low or low ICT access). The sum of these points across all sectors yielded a total CI Stock Typology score for each region, ranging from 0 to 8, thereby quantifying overall infrastructure sufficiency with respect to both spatial and population coverage. Finally, regions were classified into four groups according to their total scores: Low Sufficiency (scores 0-2), Moderately Low Sufficiency (scores 3-4), Moderately High Sufficiency (scores 5-6), and High Sufficiency (scores 7-8).

Table 2. Typology Calculation

CI Stock Typologies per Sector	Points Assigned
High–High (Transport, Energy, Public Services), High (ICT)	2
High–Low or Low–High	1
Low–Low (Transport, Energy, Public Services), Low (ICT)	0

4. Findings

The composite indicator of critical infrastructure stock reveals notable spatial disparities across EU NUTS-2 regions. Regions in Central and Northern Europe, particularly parts of Germany, Scandinavia, and the Benelux countries, consistently show the highest composite CI stock scores, reflecting a combination of transport networks, energy supply, ICT and public service infrastructure. Contrarywise, much of Southern and Eastern Europe, including many regions in Spain, Portugal, Greece, and Eastern member states, appear in the lower ranges of the index. These areas are often characterized by sparser infrastructure networks and lower levels of service provision, especially in transport and public services.

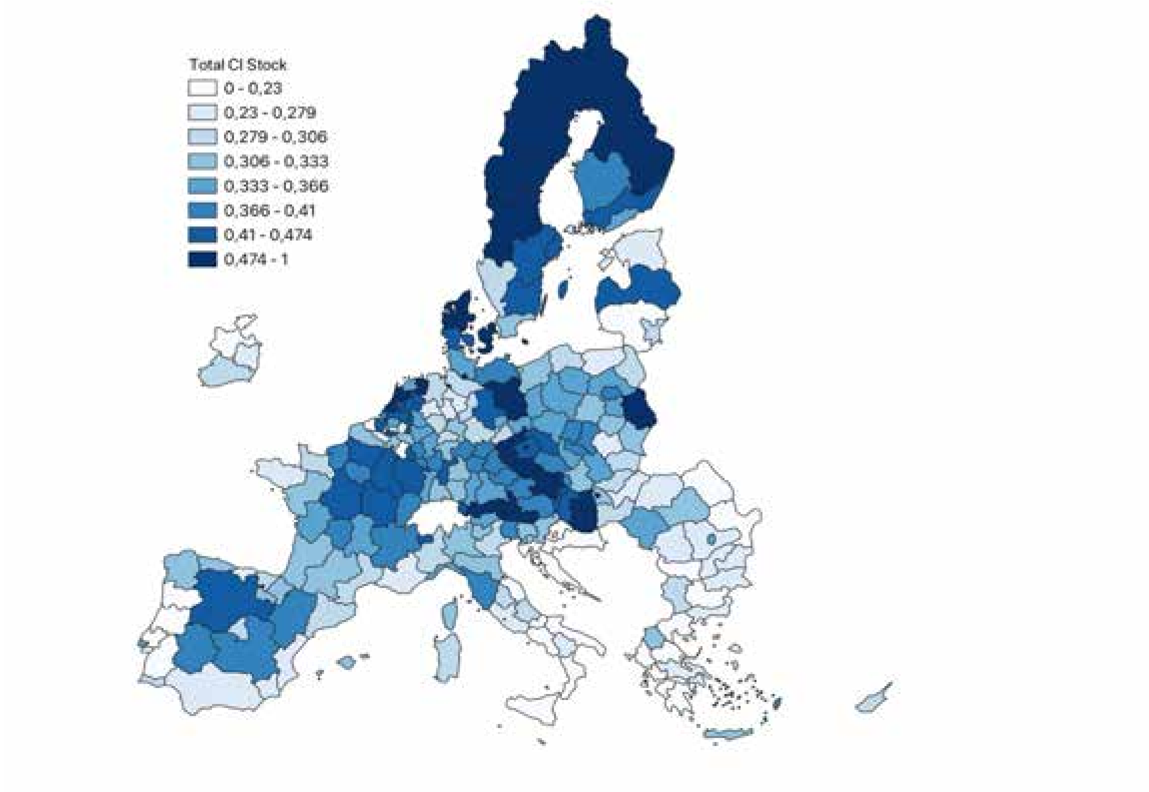

Figure 1. Total CI Stock Scores of NUTS 2 Level Regions in EU

The map further highlights that CI stock is not uniformly distributed even within countries. For instance, certain metropolitan or capital regions may achieve higher scores due to agglomeration effects and concentrated investments, whereas more peripheral or rural areas often lag behind.

Another important insight is that strong performance in one sector does not necessarily correlate with strength in others. For example, Portuguese regions exhibit high scores in energy infrastructure but tend to fall below the EU average in ICT and public services. Likewise, the Andalucía region in Spain demonstrates average performance in energy infrastructure but scores very low in transport and public services which could limit the actual accessibility of these services during critical moments.

To further explore the distribution of CI sufficiency across regions, we applied CI Stock Classification using sectoral medians as reference thresholds. Four categories were defined: High Sufficiency, Moderately High Sufficiency, Moderately Low Sufficiency, and Low Sufficiency.

Figure 2. CI Stock Typologies of NUTS 2 Level Regions in EU

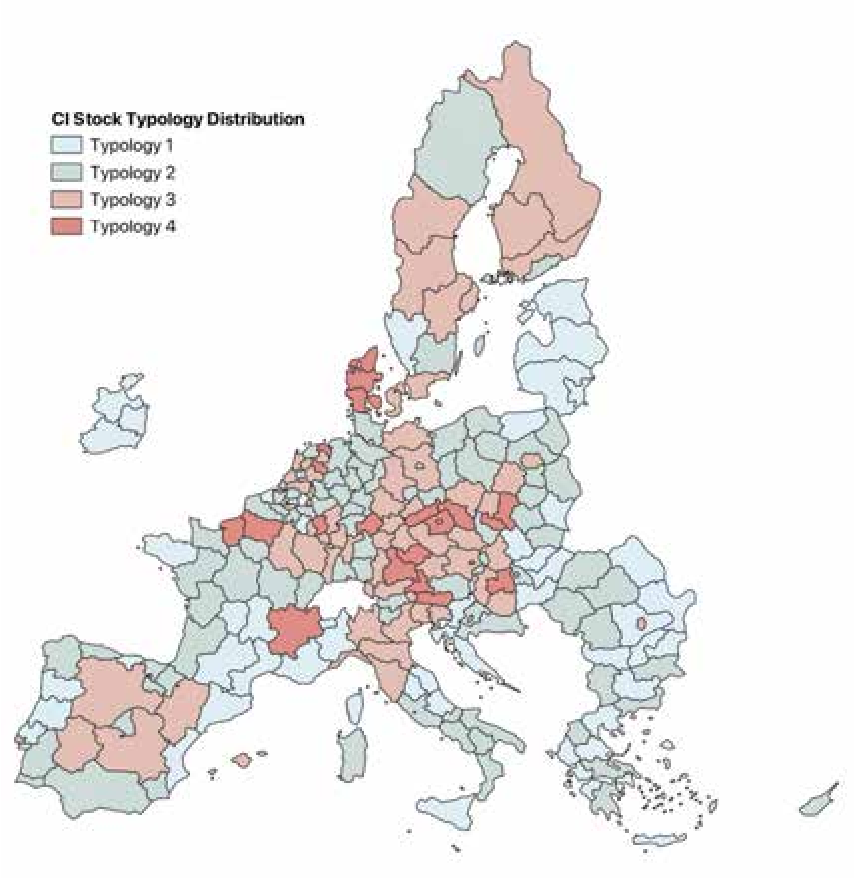

Table 3. Frequencies of CI Stock Typologies

CI Stock Typologies	Frequency	Percent
1. Low Sufficiency (0-2 points)	53	22.65%
1. Moderately Low Sufficiency (3-4 points)	92	39.32%
1. Moderately High Sufficiency (5-6 points)	68	29.06%
1. High Sufficiency (7-8 points)	21	8.97%
Total	234	100.00%

The distribution of CI Stock Typologies indicates that the majority of regions fall into the lower sufficiency categories. Specifically, 22.7% of regions are classified as having low sufficiency (0-2 points), while 39.3% are in the moderately low sufficiency group (3-4 points). Moderately high sufficiency (5-6 points) is observed in 29.1% of regions, and only 9% of regions achieve high sufficiency (7-8 points).

This pattern suggests that a significant proportion of regions have limited or only moderate levels of critical infrastructure provision, with relatively few regions exhibiting comprehensive infrastructure sufficiency across all dimensions. The findings highlight potential disparities in infrastructure availability and point to areas where targeted policy interventions may be necessary to enhance regional resilience.

6. Discussion

The findings highlight significant cross-regional variation. While some regions exhibit balanced and robust infrastructure profiles, many show asymmetries or sector-specific gaps. Importantly, the clustering analysis reveals that most regions fall within moderate sufficiency categories, combining strengths in some sectors with weaknesses in others. This diversity underscores the need for differentiated policy approaches and reinforces the argument that contribution to regional resilience cannot be determined by single-sector performance but by the interplay of multiple critical infrastructure systems.

Within Central Europe, capital regions such as Berlin, Prague, and Vienna emerge as concentrated CI hubs. High scores in these areas may partly reflect their political, economic, and institutional centrality. These regions have historically benefited from sustained investment, higher population densities, and strong institutional frameworks that support infrastructure expansion and maintenance. Similarly, certain peripheral regions in Nordic countries as parts of Sweden and Finland also exhibit high infrastructure scores. This could be attributed to their large geographic size and the extensive spatial coverage of infrastructure, especially transport systems connecting distant settlements to central nodes. A closer look reveals that these regions perform well in the transport and energy sectors, reinforcing the interpretation that both spatial reach and redundancy contribute to their higher resilience potential.

When comparing the composite infrastructure score map with the sufficiency classification, a broad west–south divide remains visible; however, several regional-level differences emerge. At first glance, these may appear to result from the exclusion of electricity line data in the second analysis. Yet, closer inspection reveals deeper structural nuances. For instance, Latvia appears relatively well-positioned in the composite CI stock map, but falls into the Low Sufficiency category upon typology classification. This reflects that while infrastructure quantity may be present, its relative redundant capacity across all critical infrastructure sectors may still be low. Similarly, while regions in Sweden and Finland continue to score high in the composite CI stock indicator, the sufficiency classification reveals certain shifts. These changes suggest that although these regions benefit from high overall CI levels, they may not consistently score high across all four sectors, which indicates insufficiencies in planning. In contrast, Danish regions display more stable patterns across both maps, suggesting a more uniformly distributed and sufficient critical infrastructure stock.

Regions with low CI sufficiency, particularly in Southern and Eastern Europe, may face serious challenges in service continuity and recovery under disruptive conditions. In contrast, capital cities and some larger northern areas benefit from higher levels of sufficiency, though even these may be reliant on centralised nodes or infrastructure corridors that pose vulnerability in cases of failure.

A study by Stanickova & Melecky (2018), built a broad composite index of regional resilience, the most resilient regions were largely in Northern and Western Europe – Scandinavian countries and Western EU regions scored the highest on the resilience index. By contrast, the least resilient were concentrated in the south: the authors note that the "southern circuit" (Portugal, Spain, Italy and Greece) showed the lowest resilience scores among EU regions. The findings in our paper similarly reveal a north/centre–south divide excluding Spain. However, this difference can also be explained by the fact that certain southern European regions have invested in extensive transport and energy networks (partly through Cohesion Policy), so they may not rank at the very bottom in our study based on critical infrastructure. Our findings for Finland and Sweden, on the other hand, invite a reflection on the argument made by Pursiainen (2018), who highlights an emergence of a Nordic model of critical infrastructure resilience. This "nordic model" is characterised by redundancy, preparedness, multi-actor cooperation, and a stronger focus on maintaining functionality over protecting specific assets. According to his study, the Nordic approach combines robust public institutions with cross-sectoral coordination and adaptive governance. These structural and institutional features may help explain the higher infrastructure scores and relative consistency observed in regions of Finland and Sweden in our analysis.

8. Conclusion

This study investigated the distribution of critical infrastructure stock across EU NUTS-2 regions, employing a composite indicator encompassing four essential sectors: transport, energy, ICT, and public services. CI indicators were standardized by both population and land area, ensuring that both demographic accessibility and spatial coverage were taken into account. In a subsequent analytical step, regions were classified into four distinct categories based on sectoral median thresholds, allowing for a nuanced comparison of infrastructure sufficiency across the European context.

The findings reveal significant spatial disparities. While some regions (particularly in Central and Northern Europe) exhibit consistently high critical infrastructure scores, others, especially in Southern and Eastern Europe, show notable gaps or unbalanced profiles. Regions located in central Europe like Berlin, Vienna, Prag and parts of Sweden and Finland benefit from high spatial reach and sufficiency, particularly in transport and energy. In contrast, Southern regions may have strong energy capacity due to natural resources but often underperform in transport and public services. A key insight is that strength in one sector does not guarantee strength in others. Many regions exhibit a mix of high and low performances, highlighting the need for just critical infrastructure provision and regional planning. The classification results confirm this: only 9 percent of regions fall into the high sufficiency category, while nearly one-quarter face serious gaps. Most regions occupy an intermediate space, with strengths in some areas but weaknesses in others.

However, this study has limitations and the principal limitation concerns data availability. Critical infrastructure data is often difficult to access due to security concerns and the fact that much of it is managed by private entities. While the use of OpenStreetMap (OSM) data is common in similar research, its reliability may be affected by its reliance on user-contributed reports, highlighting the need for further data verification. The predominance of private sector operation in many CI sectors also presents a significant barrier to accessing comprehensive open data.

Furthermore, as previously discussed, the definition and prioritization of what constitutes critical infrastructure can differ substantially between nation states' agendas. Looking ahead, an important step would be to identify, through broader studies, those critical infrastructure sectors that provide essential services that are mainly for public good and are as independent as possible from state and market interests. On this basis, developing a more expansive composite indicator including additional sectors based on public perceptions of essential services, such as housing or elderly services, could enhance the assessment of CI sufficiency and societal resilience.

Lastly, while this study primarily addresses the sufficiency of critical infrastructure, future research should also examine other dimensions emphasized in the literature, such as connectivity and redundancy, to provide a more holistic assessment of regional resilience. Additionally, future research could benefit from experimenting with alternative clustering methods such as hierarchical clustering, k-means, or density-based approaches to explore whether different techniques yield distinct or more nuanced typologies of CI provision. Comparing results across multiple clustering methods could provide deeper insights into the robustness and sensitivity of regional classifications and their implications for policy.

In sum, this study demonstrates the value of moving beyond single-sector or investment-based assessments toward a more spatially grounded, cross-sectoral understanding of critical infrastructure. The composite indicator developed here offers a useful practical tool for identifying vulnerabilities and guiding resilience-focused regional planning. As regions face growing environmental and socio-economic risks, ensuring the sufficiency of critical infrastructure will be essential for building more resilient regions.

References

Afgan, Naim, and Ayfer Veziroglu (2012). "Sustainable resilience of hydrogen energy system. International Journal of Hydrogen Energy, 37(7), pp. 5461-5467.

Akbarzadeh, Meisam Memarmontazerin, Soroush, Derrible, Sybil, & Salehi Reihani, Sayed Farzin (2019) The role of travel demand and network centrality on the connectivity and resilience of an urban street system. Transportation. 46, pp. 1127-1141.

Bauer, Gerry, Behrens, Ulf, Bowen, Matthew, Branson, James, Bukowiec, Sebastian, Cittolin, Sergio, Coarasa, Jose Antonio, Deldicque, Christian, Dobson, Marc, Dupont, Aymeric et al. (2012) High availability through full redundancy of the CMS detector controls system, Journal of Physics: Conference Series, 396, p. 012041

Boh, Waifong, Constantinides, Panos, Padmanabhan, Balaji, Viswanathan, Siva (2023) Building digital resilience against major shocks. Mis Quarterly 47(1) pp.343-360.

Borgatti, Lisa. (2008) Pacific islands' bilateral trade: the role of remoteness and of transport costs. Journal of International Development: The Journal of the Development Studies Association 20(4) pp. 486-501.

Boschma, Ron (2015) 'Towards an evolutionary perspective on regional resilience'., Regional Studies, 49(5), pp. 733–751.

Bröcker, Johannes. (2009) Infrastructure and regional development. Jahrbuch für Regionalwissenschaft, 29(1), pp. 3–21.

Burgess, J. Peter, (2007). Social values and material threat: the European Programme for Critical Infrastructure Protection. International journal of critical infrastructures, 3(3-4), pp.471-487.

Canning, David (1998). A Database of World Infrastructure Stocks, 1950–1995. World Bank Economic Review, Working Paper.

Chopra, Shauhrat S., Khanna, Vikas (2015). Interconnectedness and interdependencies of critical infrastructures in the US economy: Implications for resilience. Physica A: Statistical Mechanics and Its Applications (436) pp.865–877

Deelstra, Andrew, and David N. Bristow (2023) Assessing the effectiveness of disaster risk reduction strategies on the regional recovery of critical infrastructure systems Resilient Cities Struct, 2(3), pp. 41-52.

Demirel, Hande, Mert Kompil, Mert and Françoise Nemry, Françoise. (2015) A framework to analyze the vulnerability of European road networks due to Sea-Level Rise (SLR) and sea storm surges. Transportation Research Part A: Policy and Practice. (81) pp. 62-76.

DGAP (2023) Mapping the World's Critical Infrastructure Sectors. DGAP Policy Brief, No. 35, November 2023. German Council on Foreign Relations. [Online] available at: https://dgap.org/en/research/publications/mapping-worlds-critical-infrastructure-sectors

European Commission (n.d.) Critical infrastructure resilience at EU level. [Online] Available at: https://home-affairs.ec.europa.eu/policies/internal-security/counter-terrorism-and-radicalisation/protection/critical-infrastructure-resilience-eu-level_en

Forcellini, Davide (2023) The role of redundancy of infrastructures on the seismic resilience (SR) of sustainable communities." Sustainability 15(15) pp.11849.

Gallais, Cecilia, and Filiol, Eric (2017) Critical infrastructure: Where do we stand today? A comprehensive and comparative study of the definitions of a critical infrastructure. Journal of Information Warfare, 16 (1), pp.64–87.

Hickford, Adrian J., et al. Blainey, Simon P., Ortego Hortelano, Alejandro and Pant, Raghav (2018) Resilience engineering: theory and practice in interdependent infrastructure systems. Environment Systems and Decisions 38(3) pp. 278-291.

Huddleston, Pippa., Smith, Tim., White, Ian. and Elrick-Barr, Carmen. (2022) Adapting critical infrastructure to climate change: A scoping review, Environmental Science & Policy (135), pp. 67–76.

Hwang, Hwee, Alicia Forrester, Alicia, and Kevin Lansey, Kevin. (2013) "Resilience of regional water supply systems." World Environmental and Water Resources Congress 2013: Showcasing the Future.

Ke, Siao-Syun, & Hsu, Chih-Hao (2022). Developing a Disaster Chain Method to Evaluate Transportation Systems: A Pilot Study of Predicting Debris Blockages in Disaster-Response Road Systems. Transportation Research Record, 2677(1), pp. 475-489.

King, Abby C., Sallis, James F., Frank, Lawrence D., Saelens, Brian E., Cain, Kelli, Conway, Terry L., Chapman, James E., Ahn, David K., Kerr, Jacqueline (2011) Aging in neighborhoods differing in walkability and income: associations with physical activity and obesity in older adults. Social science & medicine 73(10) pp. 1525-1533.

Larkin, Brian. (2013) The politics and poetics of infrastructure. " Annual review of anthropology (42). pp.327-343.

Martin, Ron, and Peter Sunley. (2015) On the notion of regional economic resilience: conceptualization and explanation. Journal of economic geography. 15(1) pp.(2015): 1-42.

Michaela Stanickova, Michaela, & Lukás Melecky (2018) Understanding of resilience in the context of regional development using composite index approach: the case of European Union NUTS-2 regions, Regional Studies, Regional Science, 5(1) pp. 231-254.

Moteff, John D., and Resources, Science, and Industry Division. (2007) Critical infrastructures: Background, policy, and implementation. Congressional Research Service, Library of Congress.

Newbill, Colleen M. (2019) "Defining critical infrastructure for a global application." Ind. J. Global Legal Stud. (26) pp.761.

Nirandjan, Sadhana, Koks, Elco E., Ward J. Philip, Aerts, Jeroen C.J.H. (2022) A spatially-explicit harmonized global dataset of critical infrastructure. Scientific Data 9(150)

Onda, Kyle, Crocker, Jonny, Lyn Kayser, Georgia, Bartram, Jamie (2014) Country clustering applied to the water and sanitation sector: A new tool with potential applications in research and policy. International journal of hygiene and environmental health 217(2-3) pp. 379-385.

Pant, Raghav, Scott Thacker, and Jim W. Hall. (2017) System-of-systems framework for global infrastructure vulnerability assessments. Environmental Change Institute (ECI), GGKP Annual Conference. 2017.

Redding, Stephen J. and Turner, Matthew A. (2014) Transportation costs and the spatial organization of economic activityy'. Handbook of Regional and Urban Economics (5)s, 5, pp. 1339–1398.

Reggiani, Aura, Nijkamp, Peter and Lanzi, Diego (2015) Transport resilience and vulnerability: The role of connectivity. Transportation research part A: policy and practice. 81. pp. 4-15.

Sheffi, Yossi (2005) Preparing for the big one (supply chain management). Manufacturing Engineer (84) pp.12-15.

Shi, Yijun, Y. Zhai, Guofang Zhai., Xu, Lihua., Zhou, Shutian., Lu, Yuwen., Liu, Hongbo., and Huang, Wei. (2021) Assessment methods of urban system resilience: From the perspective of complex adaptive system theory. Cities, (112) pp.103141.

Sitzenfrei, R., obert, Mair, Maximilan, Möderl, Micheal, Rauch, Wolfgang (2011) Cascade vulnerability for risk analysis of water infrastructure." Water Science and Technology 64.9(9) pp. 1885-1891.

Sun, Wenjuan, Bocchini, Paolo and Davison, Brian D. (2018) Resilience metrics and measurement methods for transportation infrastructure: the state of the art. Sustainable and Resilient Infrastructure, 4(3), pp.144–168.

Thévenaz, Céline, and Sandra L. Resodihardjo (2010) All the best laid plans... conditions impeding proper emergency response. International Journal of Production Economics 126(1) pp. 7-21.

Trojanowski, Piotr, Husár, Jozef, Hrehová, Stella, Knapčíková, Lucia (2024) Cluster Analysis as a Basis for the Development of an Application Assessing the Reliability of Transport Infrastructure. Mobile Networks and Applications 29(3) pp.981-990.

Wendy Elizabeth Steele, Karen Hussey & Stephen Dovers (2017) What's Critical about Critical Infrastructure Urban Policy and Research 35(1), 74-86.

Xu, Tian-Shi, Hsiao-Dong, Chiang, Liu, Guang-Yi, Tan, Chin-Woo (2015) Hierarchical K-means method for clustering large-scale advanced metering infrastructure data. IEEE Transactions on Power Delivery 32(2) pp. 609-616.