Aligning social, environmental, and economic externalities of critical infrastructures with utilities' resilience and public interest

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Abstract

Critical infrastructures (CIs) provide essential services, such as energy and water supply, that support the core functions of the economy and society. These services generate positive external effects, like well-being and economic performance, and negative external effects, like service interruptions or pollution, which are not always reflected in their price. These effects vary in scale across market and non-market interactions, highlighting the public good and common-pool resource nature of CIs.

This article examines how CIs in the energy and water sectors account for public costs and benefits when adopting innovative technologies to enhance resilience and service sustainability. A social, economic, and environmental impact assessment was conducted to analyze how CI operators consider and implement international regulations related to services with public good characteristics. Based on qualitative interviews and surveys, the study identifies misalignments and opportunities regarding CIs' strategic and operational practices and existing policies.

Based on this analysis, we recommend: i) the development of multi-level "public interest" indicators, ii) balancing public and private responsibility for service resilience costs, iii) fostering collaboration across governance levels, and iv) aligning national and EU policies. Full market internalization of external costs or benefits may be limited due to varying societal spillover effects. Regulation of utilities and public financial support for the provision of services may be justified or needed in such a case. Addressing collective and individual needs, along with collaboration between public and private actors, is essential for developing measures that deal with broader spillover and cascading effects of CIs' service provision.

Keywords: public goods, impact assessment, utilities resilience, technology adoption, cascading externalities

1. Introduction

A succession of recent disasters, especially of an environmental nature (floods, droughts, and storms), has exposed the significant dependency of European societies on the uninterrupted provision of essential services. These services of general interest encompass a wide range of systems, including energy and water supply, transport networks, and health and social services (Constantin et al., 2023). They are collectively referred to as Critical Infrastructures (CIs) due to their pivotal role in supporting the reliable functioning of the economy and society (European Commission, 2025).

The resilience of these CIs is a critical factor in safeguarding societal stability, public health, and economic continuity. Resilience in this context refers to the ability of CI systems to prepare for, absorb, recover from, and adapt to adverse conditions (Curt & Tacnet, 2018). It is critical that European CIs possess not only resilience but also the capacity to adapt to evolving risks and the agility to swiftly recover from both anticipated and unforeseen disruptions. Despite the rapidly evolving threat landscape and the increasing complexity and digitalization of CI interconnectedness in Europe, CI operators and public authorities, however, are still in the process of developing comprehensive strategies to manage these risks.

The governance of public goods provision by public or semi-public utilities differs from private companies' management and provision of pure private goods. CIs as utilities must ensure the reliable provision of essential services of general interest to the economy and society (Constantin et al., 2023). These essential services are either pure public goods (non-excludable and non-rival in consumption) or common-pool resources that are non-excludable but rival in consumption, such as drinking water or electricity supply at peak load (Frischmann, 2004; Kimmich, 2013; Kimmich & Sagebiel, 2016; Moss et al., 2013). Service undersupply or interruption may occur if there is congestion or overuse of resources.

These infrastructures exert negative and positive external effects on third parties, and the related costs or benefits are normally not included in the transaction price (De Paoli et al., 2010). Positive effects relate to the secure and sustainable provision of essential services to all, promoting (regional) economic development, and enhancement of social well-being. Negative effects relate to undersupply, overuse of resources, disruption of essential service provision, unequal supply, and environmental harm (air pollution and emission of greenhouse gases). To capture the size and scale of positive or negative externalities, it is important to consider not only the effects of market transactions, but also the spillover effects of nonmarket social interactions (Paniagua & Rayamajhee, 2024). A broader understanding of the effects of service interruption due to unexpected risks such as extreme weather events, climate change, or pandemics includes effects on the whole economy through indirect, spillover, and cascading effects. It is crucial to enhance utilities' resilience, considering the broader consequences, to guarantee a reliable supply.

Impact assessments of services' provision require evaluating public costs and benefits of resilience measures, including the adoption of innovative technologies. While impact assessments of new technologies are important (Mulder, 2013), many current impact assessment technological solutions are narrowly focused on isolated aspects of sustainable development, failing to address the broader societal impacts (Ward et al., 2019). Public interest indicators in the governance of utilities remain limited (Yurrita et al., 2022). To address this research gap, we identify the economic, social, and environmental impacts of utilities across multiple scales (micro, local, regional, national) as important dimensions for developing resilient and sustainable CI strategies.

Operating under various national and European regulations, CIs often have public contracts and are financially supported and regulated by governments, because they provide public goods or common-pool resources (Kimmich, 2016; Mazzucato, 2024).

Although regulations governing the provision of services of general interest vary across sectors and countries, they are guided by shared principles concerning resilience, efficiency, social responsibility, and sustainability. Achieving coherence across CI sectors is challenging as there is a need for harmonized standards and practices for security, risk assessment, resilience measures, and improved coordination between public and private governing bodies. These challenges stem from varying levels of regulation across CI sectors and the difficulty of developing long-term resilience strategies capable of addressing emerging threats. Developing shared perspectives on implementing resilience measures within risk assessment remains a central priority (Guo et al., 2021). Considering the external effects of adopting new technologies within regulatory frameworks is essential for promoting innovation and enhancing efficiency. However, for technologies with significant spillover effects, a case-by-case analysis is more relevant (Marques et al., 2022).

The main objective of this paper is to identify misalignments between CIs' practices and priorities stated in policy documents regarding resilience and sustainability of CIs as public goods providers. On this basis, policy conclusions are offered.

The main research questions are: i) To what extent do CIs consider externalities (broader social, environmental, economic impacts) when deciding whether to adopt new technologies for enhancing resilience?; ii) How do CIs' decision-making perspectives on externalities and public value align with regulations regarding resilience of critical entities and empirical impact assessments (e.g. in public-private partnership contexts)? iii) Who is responsible for the financial support for this improvement in CI resilience (CIs' internal budgets, public subsidies or other sources)?

To answer these questions, we make use of the Horizon Europe SUNRISE project[1] (2022) that develops technological solutions for CI resilience. The project is designed to tackle the challenges of ensuring the continuity and accessibility of critical services in Europe. This is to be achieved through the development and implementation of innovative technological solutions aiming to enhance the adaptability and reliability of CIs. The project's consortium includes 18 public and private CI operators and regulators from diverse sectors (energy, transport, health, digital infrastructure, water supply, and public authorities) from EU Member States and associated countries. The present analysis focuses on two sectors: energy and water supply. They were selected because: (i) they constitute the primary agents of technological solution adoption in the project; and (ii) the research team possesses specialized expertise in these areas. The analysis deals with two technological solutions developed within the project: (i) Demand Prediction and Management (DPM) offering flexibility in managing changing resource demands during emergencies; and (ii) A Remote Physical Infrastructure Inspection (RII), which utilizes satellite images, unmanned aerial vehicles (UAVs) equipped with various sensors, and machine learning to detect anomalies and continuously inspect physical infrastructures. These solutions were selected based on their high relevance to the targeted sectors. Implementing technical solutions can have diverse social, economic, and environmental impacts, so setting up the right assessment framework is crucial.

2. Public goods theory, externalities, and impact assessment

2.1. Externalities, theories on public goods, and governance

The security of supply of essential services − both for industry and end-users − has become a central policy issue, especially in light of the Covid-19 pandemic and the growing need to be prepared for future crises (Fabra et al., 2020). A study by Baik et al. (2021) stresses the importance of considering the full spectrum of power interruption costs in utility planning and

[1] SUNRISE - Strategies and Technologies for United and Resilient Critical Infrastructures and Vital Services in Pandemic Stricken Europe, https://sunrise-europe.eu/sunrise/.

decision-making processes to ensure reliable and resilient service provision. While direct and short-run costs are significant, it is important to account for long-term economic losses, including indirect and spillover effects on local and regional economies, particularly those resulting from extreme natural events. Integrating these long-term considerations into energy utility planning is essential for enhancing grid resilience and guiding future investment decisions. Regarding the water supply sector, the social and economic costs resulting from inadequate water supply in extreme situations (large-scale fires), can be far-reaching, including effects on agricultural economy and food security. These risks are intensifying due to ongoing climate change. Social and environmental costs must be considered to ensure a comprehensive and sustainable approach towards governing and implications of essential service operation.

Our impact assessment framework uses principles of the economic theory of externalities and public goods. The typology of economic goods as private or public is related to the regulation of the mechanisms of their provision and consumption. According to the economic literature, there are two main criteria for classifying a good as public, private, or in different intermediary categories: a) "rivalry in consumption" and b) "excludability from consumption" (Samuelson, 1954; Samuelson & Nordhaus, 1992). Public goods are non-rival in consumption (the utility of consumption of a good does not diminish with the number of consumers) and non-excludable (the limitation of the degree of consumption of a good is limited by the price). Examples are open-access public roads with no congestion or electricity infrastructure below peak demand. On the opposite side are private goods that are rival in consumption and excludable. Common-pool resources are non-excludable, but subtractable in consumption (e.g., drinking water, electricity infrastructure under peak load demand, or public roads under congestion), while club or toll goods (e.g., cable TV, toll public roads) are not subtractable, but accessible only to customers who pay an access price for using the services that they enable (E. Ostrom, 1990).

To understand critical infrastructures as public goods or common-pool resources, it is essential to consider not only the direct benefits derived from the use of the specific infrastructure, but also the considerable indirect benefits that other people (or society in general) derive from the use and provision of the infrastructure. The importance of emphasizing the characteristics of CIs services as public good or common-pool resources is related to the external effects (costs or benefits to third parties) of their supply: a) positive effects are related to the secure and sustainable provision of essential service to all: (regional) economic development, social well-being and b) negative effects refer to undersupply, congestion, or disruption of essential service provision; non-secure and unequal supply; air pollution (greenhouse gas emissions are already partly internalized in the price).

While neither private companies nor public entities may efficiently provide public goods alone (Holcombe, 1997), they can do so when contracted or regulated by the public sector (V. Ostrom et al., 1961). In such arrangements, the government ensures effective regulation for funding and access, while leveraging private sector expertise and efficiency. Public companies often provide services of general interest. Public support and regulations are needed to correct "market failures", account for externalities and "social costs" (De Paoli et al., 2010), and ensure the provision of the publicly desired public goods. Governments at different levels (e.g., local or national level) provide support (financial aid or tax reductions) and create incentives for the organizations providing public goods.

Besides external effects based on market transactions (De Paoli et al., 2010), it is also important to take into consideration social interrelations that do not refer to market-based transactions, to consider the size and scale of positive or negative externalities (Paniagua & Rayamajhee, 2024). This concept goes beyond the "market-state-dichotomy" and includes a variety of institutions such as "complex markets, voluntary associations, governments, or other hybrid institutions" involved in interaction or transaction processes to deal with "large-scale externalities" (ibid, 2024). This is important in relation to the governance and responsibility for the costs and benefits generated by the provision of infrastructure and related services.

Regarding the energy and water sectors studied, it is important to distinguish between private versus public good elements within the production and provision systems. This distinction helps clarify the need for governance and policies on local, national, and global levels (Karlsson-Vinkhuyzen et al., 2012; Moss et al., 2013). These services rely on integrated production, delivery, and infrastructure system elements. Energy system components exhibit characteristics of both private goods (energy production) and public goods (sustainable energy systems). According to Frischmann (2004), it is important to distinguish the supply and demand sides regarding essential services. With the privatization process, private companies and market mechanisms play an increasing role, while the government plays the role of provider, coordinator, or regulator of infrastructures. The output of infrastructures is public and provides nonmarket goods, generating positive externalities that benefit society. Supply-side issues related to infrastructures are: (i) excludability; (ii) natural monopoly; and (iii) anticompetitive behavior. The demand for goods provided by infrastructures concerns issues such as non-rivalry in consumption and the use in downstream production processes and additional fields of end-use. The social value of infrastructure is thus broadly defined. Further demand-side aspects concern access to services for different user groups.

In the present paper, we use the concept of "external effects" related to the services provided by CIs. They refer to the wider economic, social and environmental impacts, as well as the public value that these services have on the economy and society.

2.2. Impact assessment: a theoretical framework

Organizations managing CIs increasingly adopt advanced technologies to enhance resilience and protect assets. Impact assessment plays a crucial role in planning and implementing technological solutions, enabling a systematic understanding of how these technologies influence organizational performance and broader societal outcomes, including social, environmental, and economic externalities. New technologies can significantly influence economic performance, environmental conditions, and social factors depending on their purpose and operation (Vanclay et al., 2015). This multifaceted impact aligns with the Triple Bottom Line approach to sustainability, emphasizing the integration of social, economic, and environmental dimensions (Purvis et al., 2019). Whilst many assessments remain compartmentalized, evaluating environmental, social, and economic impacts separately at late project stages (Bice, 2020), this study advocates for a comprehensive approach. Holistic frameworks encompass sustainability impacts, including how technologies advance sustainable development goals and address resource and policy constraints (Leal Filho et al., 2022). Integrated approaches reveal trade-offs between impact dimensions and address complex interactions between technology, human factors, and socioeconomic environments (Argyroudis et al., 2022; van Gemert-Pijnen et al., 2011). This is particularly important for project-based assessments analyzing multiple technologies within a single framework (Zherdev et al., 2024).

Simultaneous evaluation of different technological solutions requires integrated, multi-criteria approaches. The present study employs a holistic, tailored approach considering technological specificities whilst incorporating sustainability dimensions to capture long-term impact in real-world settings. This is achieved through surveys and interviews, maintaining a similar structure whilst containing specific questions for each technological solution. Results are based on the continuous impact assessment framework of SUNRISE project (2022), which relies on iterative feedback loops enabling systematic incorporation of end-user input (Gooding et al., 2021). Reconciling diverse user requirements and translating feedback into actionable changes remains challenging (Damschroder et al., 2022).

Meaningful end-user involvement through participatory approaches is a key component of impact assessment (Valentin et al., 2018), ensuring solutions are relevant for resilience strategies (Davidson et al., 2022). However, the participatory dimension is often underemphasized in practice, highlighting the importance of careful consideration of implementation goals and end-users. This analysis considers various organizational units within CIs, including operators and regulatory authorities. This user-centered perspective enables a comprehensive understanding of the sector's preparedness and adaptive capacity facing systemic disruptions.

To enhance impact assessment quality, participatory approaches should be tailored to utilities' specific characteristics as CI providers (Zherdev et al., 2024). Utilities are highly interconnected; disruption in one (e.g., electricity) can impair others (e.g., water, communications), amplifying failure impacts (Heino et al., 2019). Infrastructure complexity and uncertainties about hazards, system responses, and human behavior make predicting public impacts difficult, with uncertainties multiplying from hazard occurrence to societal outcomes. This underscores the crucial role of impact assessment for wider externalities and public good provision. A project-based framework enables evaluation of not only proposed solutions but also wider impacts, including decision-making incentives and constraints. When essential resources become scarce, CIs must foster user self-regulation mechanisms, aligning with Ostrom's (1990) common-pool resource governance, emphasizing shared responsibility.

This study applies an impact assessment framework examining CI management from both provider and user perspectives, ensuring access to shared resources essential for societal functioning. This approach is crucial for understanding the scaling potential of newly developed technological solutions and related governance structures beyond pilot stages, requiring Pareto-improving strategies where no participant can improve welfare without reducing another's (Cornes & Sandler, 2000).

This analysis focuses on the impact of CIs' provision of services using new technologies on security of supply, disaster resilience, regional and local economic development, and general population well-being. It considers regulations, public support and policies at various levels to be factors that support CIs.

2.3. Policy context and regulations

Within the present article, international frameworks were prioritized over national-level regulations due to their broader applicability and potential for cross-border implementation. The supranational nature of these documents ensures that the study's findings and methodologies can be generalized beyond specific national contexts, thereby enhancing the transferability and scalability of the research outcomes. The regulations provide standardized definitions and metrics that facilitate comparative analysis across different national jurisdictions, which would not be possible with country-specific regulatory approaches.

The European Commission's Critical Entities Resilience (CER) Directive came into effect on October 18th, 2024 (2022). This directive established a comprehensive framework that aims to strengthen the resilience of critical entities to ensure the provision of essential services to the public, including energy, transport, banking, financial market infrastructures, health, drinking water, wastewater, digital infrastructure, public administration, space, and food sectors. Today, nations across the EU are adopting national laws that will identify critical entities and lay out their legal obligations regarding the prevention, protection against, response to, resistance to, mitigation, absorption, accommodation, and recovery from a disruptive incident.

The CER Directive requires national governments to conduct risk assessments and develop long-term resilience strategies. The critical entities themselves are obliged to identify relevant risks, take measures, and notify authorities of disruptive incidents (European Council, European Parliament 2022).

Complementing this European framework is a global perspective provided by the United Nations Office for Disaster Risk Reduction (UNDRR). In its publication "Global Methodology for Infrastructure Resilience Review" (2023), the UNDRR outlines measures that a nation could proactively take to minimize the economic and human losses a disruption to infrastructure could have. The framework they propose consists of 5 steps: (i) Map institutional governance and identify key stakeholders; (ii) Review existing policies and regulations; (iii) Detect vulnerabilities through a stress-testing analysis; (iv) Assess current resilience through the Principles for Resilient Infrastructure; and (v) Develop an implementation plan and produce a final report (Global Methodology for Infrastructure Resilience Review, 2023). This framework aims to protect people who are more dependent on services provided by CI systems, including energy, transport, water, wastewater, waste, and digital communications. Social infrastructures, such as health and social care, education, police and prisons, fire and emergency services, are specifically mentioned in the UNDRR's "Principles for Resilient Infrastructure" (2022). The role of CI to protect society and the environment, enrich living standards, and stimulate economic growth is also acknowledged (ibid, 2022).

The UNDRR also emphasizes the growing complexity of hazards and the cascading effects they can have on interconnected infrastructure systems. As such, there is a need to address gaps in infrastructure planning, financing, design, development, and operation by taking a systems perspective with resilience in mind. The UNDRR's "Handbook for Implementing the Principles for Resilient Infrastructure" (2023) highlights this need in its six guiding principles. Notably, it emphasizes community engagement to reduce harmful behaviors toward infrastructure (e.g., vandalism) to enhance resilience by incorporating social justice and local knowledge (ibid, p51). The principles also mention the benefits of documenting the shared-risk-and-return in terms of the pricing of social benefits, such as quality-of-life improvements, reduced casualties, and enabling investment in other sectors (ibid, p60).

3. Methodological framework

For our analysis, we used semi-structured interviews and structured questionnaire surveys to study the complex social, economic, and environmental effects of implementing new technological solutions in CI service provision. The study employs the SUNRISE project's impact assessment framework, evaluating project impact through technological solution analysis and developing a sustainability roadmap for continued use beyond project completion (2022). It identifies technological solutions' impacts across Triple Bottom Line areas and provides policy conclusions to help CI operators mitigate negative effects and enhance technological solution benefits through continuous impact evaluation during development and pilot implementation. Understanding incentives and requirements by driving decision-making processes is pivotal for effective methodology application.

Evaluating technological solutions' implementation outcomes requires assessing enhanced CI resilience at both the infrastructure provider level and the broader societal level. This includes (1) service provision characteristics following the introduction of new technological solutions, (2) the governance and regulatory framework and strategic decision-making, and (3) the broader impact of technological solution implementation on service delivery.

The first level of outcome measure is the reliability of the infrastructure provider. The second measure is the benefits of preventative maintenance and the ability to withstand disasters – natural and human using technologies in ensuring the sustainability of shared societal and natural resources. The third level is the ability to ensure the sustainability of the service under the conditions that influence the primary resource needed to provide the service.

The main impact categories for the present analysis derive from SUNRISE impact assessment categories, defined and validated by CIs as end-users using participatory approaches to incorporate diverse perspectives, needs, and expectations in technological solution design and deployment (Zherdev et al., 2024). These categories include security of supply, resilience and long-term sustainability, financing and investment in CI, economic development impacts, costs of service interruptions, social equity, and justice in access to public goods, citizen well-being, environmental impacts, alignment with policy goals.

3.1. Methods: interviews, surveys, review of policy documents

For the analysis, we performed eight semi-structured interviews with representatives of CIs and other experts, such as technological solution developers, in the period from March to June 2025 (cf. Supplementary material A. Interview guideline). Target interviewees are decision makers within CIs in the energy (electricity) sector and in the water supply sector involved in the EU-funded Horizon Europe SUNRISE project (2022). They operate in Italy, Spain, and Slovenia.

We analyze the relevance of the criteria of reliable service provision for companies and end-customers on the regional and national levels. We examine the functions of DPM and RII technological solutions developed within the project. We focus on the resilience of the CIs regarding climate change (extreme weather events and drought). Within the semi-structured interviews, we spoke with representatives of the CIs and technological solution developers about the following topics:

- Regulatory framework for the operation of CI (including sub-topics of ownership, governance, and management structures; existence of a public contract; regulatory framework for operation)
- Service provision and implementation of new technological solutions (including sub-themes of: organizational incentives for service provision; main users of the services; social, economic, and environmental criteria considered for service provision and new technological solutions' implementation; hazard events considered for the introduction of new technological solutions; financial sources for the implementation and upgrading of new technological solutions)
- Enhancing the resilience of CIs, including the following sub-topics: organizational decision-making processes; consideration of social, economic, and environmental impacts; and metrics used to measure these impacts.

For the analysis of data, we apply a structuring qualitative content analysis (Kuckartz & Radiker, 2023). We use an approach combining deductive coding upon main categories based on the interview guideline and then build further categories upon the whole interviews' material using inductive coding. Interview transcriptions were prepared using the AI-based Software *aTrain*, licensors Armin Haberl, Jürgen Fleiß, Dominik Kowald, Stefan Thalmann (Haberl et al., 2024). The analysis is performed using Excel and MAXQDA.

The analysis has certain limitations, including self-selection bias from project partner involvement and a lack of a control group, examining only implementation advantages. Additionally, the research effect means evaluation impacts itself, which is part of the project's impact assessment methodology, incorporating continuous assessment with feedback loops.

The analysis draws also on online survey results based on a structured questionnaire from the Horizon Europe Project SUNRISE across both sectors. It includes 12 responses from CI employees - 5 RII adopters and 7 DPM adopters - representing 7 water utilities and 5 energy utilities. Given the limited sample size precluding statistical analysis and quantitative generalization, findings are presented qualitatively as emergent trends where substantial proportions identified specific impacts. This approach aligns with qualitative research principles emphasising data depth over statistical representativeness (Braun & Clarke, 2006). In small-sample qualitative studies, the focus shifts from statistical significance to theoretical significance, where patterns and themes that emerge across multiple participants can provide valuable insights into the phenomenon under investigation, even without large numbers (Mason, 2010). The presentation of findings as "emergent trends" rather than definitive conclusions acknowledges the exploratory nature of the research while still recognizing meaningful patterns in the data, providing a new understanding of the research problem. The survey was administered via the QUALTRICS platform, with results analyzed using Excel and SPSS. Questions were tailored to the specific functionality of each technological solution (cf. Supplementary material B and C: Excerpts from the questionnaires).

4. Results

Findings from interviews and surveys with participants in CIs sectors are grouped into three key thematic areas: 1. service provision characteristics following the introduction of new technological solutions, 2. the governance and regulatory framework and strategic decision-making, and 3. broader impact of technological solution implementation on service delivery. The results reveal the CIs' perspectives on the issues stated in the research questions regarding the consideration of externalities (broader social, environmental, and economic impacts) when deciding to adopt new technologies for enhancing resilience (cf. Section 3)

4.1. Service provision characteristics following the introduction of new technological solutions

Efficiency Gains and Operational Enhancements. Interviews revealed that the technological solutions significantly improve operational efficiency through multiple mechanisms. The RII technological solution enables faster infrastructure analysis, reducing maintenance time and resources, while the DPM technological solution optimizes energy consumption and costs, enhancing resource allocation. Remote inspection capabilities reduce response times and enhance decision-making, and UAV deployment reduces workforce requirements while providing prompt infrastructure data, streamlining operations across utilities.

Multifaceted Benefits and Forecasting Improvements The benefits identified refer to enhanced predictive capabilities, increased operational efficiency, improved anomaly detection and reaction times, and greater knowledge sharing and resource optimization. Forecasting accuracy was notably improved. This concerns demand prediction, leak detection and consumption optimization when using the DPM solution in the energy sector. Usability also emerged as a benefit, with user-friendly interfaces supporting accessibility and improved decision-making. The survey's results confirmed these findings, showing improved inspection efficiency (notably in energy and water), moderate relevance for routine operations, and heightened importance during disasters. Safety outcomes for RII were mixed, though drones (UAVs) were widely recognized as reducing worker exposure to hazards.

Continuity and Resilience in Service Delivery. Both technological solutions supported resilience by enabling anomaly detection, infrastructure planning, reduced downtime, and greater availability. DPM was especially effective for demand-supply balancing in remote mountainous regions and for strengthening disaster preparedness. RII was consistently linked to inspection efficiency and safety, with benefits including early anomaly detection, infrastructure protection, and mitigation of capacity reductions. Overall, both technological solutions were considered valuable for sustaining service delivery during disasters, with DPM particularly strong in forecasting and undersupply prevention, and RII in safeguarding infrastructure and reducing destruction costs. Key benefits include early detection of anomalies and infrastructure damage, and mitigation of capacity utilization reductions across both normal operations and disaster situations.

Regarding service delivery strategies during disasters, a water sector representative additionally highlighted aggregation of smaller companies as a resilience strategy, reflecting vulnerabilities exposed during the COVID-19 pandemic and emphasizing the importance of business continuity planning, risk management, and stakeholder coordination.

Regulatory and Licensing Challenges. Implementation of the RII technological solutions is shaped by regulatory frameworks. Some companies reported established approval processes involving civil aviation authorities and multiple ministries, while others anticipated licensing requirements but lacked clarity. Restrictions, such as prohibitions of Beyond Visual Line of Sight inspections, were reported as limiting monitoring efficiency. These findings underline variation in regulatory oversight and differing levels of company awareness regarding licensing requirements.

4.2. The governance, regulatory framework, and strategic decision-making

Ownership and Service Priorities. Most interviewees represented publicly owned monopolies within their respective sectors. Operating in a market-oriented environment under margin and capacity constraints was reported in the energy sector. Despite structural differences, all companies prioritized reliable service delivery as a core responsibility to citizens and industries.

Regulatory Frameworks. Governance is multi-layered, spanning EU directives, national legislation, regional oversight, and municipal permits. Sectoral differences are marked: energy utilities operate under European frameworks (e.g., ENTSO-E, Green Deal mandates) with strong emphasis on renewable integration and technical standardization, while water utilities face fragmented regulation, balancing multi-use resource management and sustainability requirements. Enforced gaps were noted, particularly in water reuse obligations, where compliance remains weak despite formal mandates.

Financing and Public Support. All cases reported reliance on public resources, though mechanisms vary. Water utilities often use EU grants, research programs, or mixed tariff-based systems supplemented by public funding, while reliance on internal budgets is expected in the energy sector. Despite heterogeneity, public resources were viewed as critical for sustaining investment.

Decision-making. Authority is shaped by governance structures. Water utilities rely on contracts with local authorities, while energy utilities are subject to oversight by transmission system operators. Digital technological solutions were widely regarded as enhancing decision-making, with survey results showing especially high ratings for RII. Concerns about overreliance were stronger for DPM, whereas RII was seen as offering more balanced decision support.

Stakeholder Engagement. External approval and political endorsement were deemed essential for project development. Both energy and water utilities stressed the importance of community and government support, with the DPM technological solution highlighted as facilitating interdepartmental coordination and communication with municipalities during crises. Survey data confirmed improved stakeholder cooperation after technological solution implementation.

Strategic Priorities. Continuity, resilience, and adaptability were central themes across sectors, underpinned by contingency planning, risk management, business continuity planning, and regulatory compliance. Companies emphasized preparedness for climate change, disasters, and operational disruptions. Aggregation of smaller utilities was proposed as a strategy to strengthen resilience, reduce costs, and expand capacity.

4.3. Wider impact of technological solution implementation on service delivery for the economy and society

Interviews and survey findings indicate that the implementation of advanced technological solutions and technologies is associated with several broader benefits, including improved supply security, enhanced resilience and sustainability, economic development, and social well-being, alongside the mitigation of environmental impacts.

Disaster preparedness. Participants stressed the role of these technological solutions in strengthening prevention and response capacities. Energy sector representatives highlighted improved disaster prediction, resource allocation, and rapid infrastructure assessment, while water sector participants noted benefits for recovery planning, anomaly detection, demand forecasting, and preparedness for droughts and floods. Overall, respondents expressed strong confidence in their effectiveness against natural hazards.

Economic impacts. All interviewees acknowledged economic benefits, particularly through improved reliability and reduced service disruption. Both DPM and RII solutions were seen to limit losses and support regional development, including tourism and irrigation. RII was noted for job transformation by shifting staff from routine tasks to higher-value roles. The survey suggested moderate potential for reducing personnel and operational costs.

Well-being and service prioritization. Companies differed in prioritization strategies, but all recognized the primacy of essential services. Water utilities maintained clear classifications of uninterruptible services, while utilities in the energy sector emphasized equitable access. Both sectors stressed protecting vulnerable groups. Water utilities highlighted social benefits through enhanced distribution security, anomaly detection, and community awareness. Survey results on spatial inequality were mixed, though many anticipated fairer resource allocations.

Ethical challenges. Data-related risks were identified as critical. Representatives of energy sector emphasized anonymization and protection of sensitive data while water utilities noted public concerns around drone surveillance, stressing transparency and GDPR compliance. Suggested mitigations included embedding impact evaluation procedures. Survey results echoed these concerns: for DPM, issues included algorithmic biases, manipulated forecasts, and cybersecurity vulnerabilities; for RII, privacy risks, data security threats, and discriminatory potential were highlighted.

Environmental externalities. Utilities reported reduced energy use and emissions through efficiency gains, predictive analytics, and the replacement of helicopter inspections with drones. Water conservation was supported by improved demand forecasting, leak detection, and optimized pumping. Survey respondents largely anticipated environmental benefits, especially reduced energy use and emissions, though expectations for water savings were mixed.

5. Discussion

Key findings from interviews and surveys are compared in this section with the policy documents presented in section 2. The comparison allows for a systematic assessment of the alignment between stakeholder perspectives and the policy priorities currently shaping CI governance. It refers to the research questions (see Section 3) regarding the alignment of CIs' decision-making perspectives on externalities and public value with the regulatory frameworks regarding resilience of critical entities, as well as the issue of responsibility for the financial support for CI resilience improvement.

While policy documents often provide a top-down articulation of strategic objectives, regulatory frameworks, and technological ambitions, interviews and surveys capture bottom-up insights into the practical challenges, opportunities, and expectations experienced by operators, regulators, and other stakeholders directly engaged with CIs.

5.1. Service provision characteristics following the introduction of new technological solutions

The results confirm that innovative technologies are pivotal to decision-making, ensuring reliable service supply, minimizing downtime, optimizing supply-demand balance, and improving operational efficiency. DMP and RII technological solutions demonstrate that technological advancement is integral to core business operations. According to policy documents, novel technology introduction is crucial: The UNDRR Principles (2022) stress that technological progress is central to business and infrastructure resilience, reducing costs whilst improving operations and recovery. The CER Directive (2022) reframes technological progress as a core business function, mandating entities to embed ICT risk management and resilience plans into daily operations through national strategies, cross-border cooperation, and harmonized standards.

Interview findings revealed that certain technological solution components may prove inadequate for utilities' operational requirements, necessitating early identification during testing and pilot phases to allocate resources effectively. From a regulatory perspective, the CER directive (2022) promotes resource efficiency by encouraging early preparedness and the reuse of existing risk assessments. It calls on Member States to support critical entities through training and guidance whilst avoiding administrative burden. Articles 10 and 11 operationalize this through financial and methodological support and cross-border cooperation to reduce duplication.

The results indicate that some licensing regulations restrict specific operations for infrastructure monitoring, e.g. Beyond Visual Line of Sight (BVLOS) inspections are not yet permitted, which limits the efficiency of infrastructure inspection. This is also emphasized in the UNDRR Principles for Resilient Infrastructure (2022): Outdated regulations can restrict innovation in CI operations. There is a need to modernize licensing and governance to enable innovative solutions while ensuring resilience and safety. The CER Directive (2022) aims to harmonize resilience requirements for CIs operators but does not address standardized licensing or innovation barriers such as BVLOS drone inspections. Licensing regimes remain governed by sector-specific EU or national rules. Operators still face fragmented requirements when deploying innovative technologies.

5.2. The governance, regulatory framework, and strategic decision-making

The analysis reveals a strong presence of government control and an increasingly integrated regulatory environment: government control, public regulation, or ownership in the provision of essential services is observed across all CI companies examined. The CIs consist of public organizations operating within various regulations. In the energy sector there exist both natural monopoly and competition, while water supply industry operates as a natural monopoly within the region of operation. This is indicative of the prioritization of the secure provision of the service as a public good over allocative efficiency or budgetary concerns and privatization. The decision-making authority held by government bodies and municipalities reinforces the public service orientation, highlighting the strategic importance of CIs for ensuring societal stability and citizen well-being.

CIs state that multi-level regulatory frameworks spanning EU directives to local requirements create complex operational landscapes varying between sectors. Energy utilities demonstrate stronger European integration through ENTSO-E membership and Green Deal compliance, with renewable energy integration providing clearer strategic direction. Water utilities face challenges managing competing demands for drinking water, irrigation, and industrial use whilst maintaining quality standards. Environmental protection and sustainable resource allocation requirements create complexity for water operators navigating fragmented stakeholder landscapes and resource-specific regulations.

According to Marques et al. (2022). regulatory schemes that consider external effects from the adoption of new technologies are important for promoting innovation and enhancing efficiency. Case-specific analyses are more relevant for technologies with higher spillovers.

The results of our analysis reveal that utilities operate within an increasingly integrated regulatory environment where EU directives drive national implementation, whilst local conditions create sector-specific challenges. Both sectors face changes from sustainability mandates requiring substantial infrastructure adaptation, necessitating significant investment in innovative technologies (such as DPM and RII technological solutions) and operational procedures.

Policy documents stress the necessity of collaboration and harmonization. The CER (2022) Directive reinforces policy coordination across the EU, national, regional, and municipal levels through integrated strategies, designated authorities, and cross-border consultations. The EU-level Critical Entities Resilience Group ensures coherence with other frameworks through harmonized multi-level governance. UNDRR emphasizes that resilient infrastructure requires coordinated governance structures and shared responsibilities across scales (Principles of Resilient Infrastructure, 2022). Multi-level governance ensures clear accountability among all actors, including private sector entities, while local and regional governments facilitate community engagement and national strategy alignment.

The results of the interviews suggest a more collaborative or mediated approach to resolving conflicts and securing approvals, rather than relying solely on formal approval processes. Companies in the energy sector emphasized the importance of stakeholder engagement and the need for support from local communities and ministries. Companies in the water sector stressed the importance of aligning with local authority investment plans. This collaborative approach extends to the approval process for new investments and projects, where companies require external validation and support. The potential for government intervention in cases of disputes, as mentioned by water producers, suggests that there is more emphasis on negotiation and consensus-building rather than purely hierarchical decision-making structures. Companies have developed different approaches to navigating regulatory and approval processes, but all of them recognize the critical importance of external validation and stakeholder support in ensuring project success.

Policy documents confirm the need for stakeholder consensus regarding risk-sharing: The Principles for Resilient Infrastructure (2022) stress the coordination, transparency, and consensus-building among stakeholders. Key actions promote collaborative management, shared responsibilities, information exchange, and transparent risk-sharing. The CER Directive places strong emphasis on stakeholder communication, coordination, and consensus-building to enhance resilience. It requires Member States to consult stakeholders in strategy development, designate single points of contact, and cooperate across borders. It is aimed to foster transparency through the Critical Entities Resilience Group and Commission support.

Furthermore, inadequate enforcement mechanisms exist regarding water reuse regulations. Despite mandatory reclaimed water use in irrigation, numerous companies fail to comply. The UNDRR Principles for Resilient Infrastructure do not explicitly address enforcement beyond critical infrastructure. Whilst water governance and wastewater management are covered through case studies, regulatory enforcement remains a gap. The CER Directive (2022) subjects drinking water and wastewater operators to supervision and enforcement as critical entities. Member States must empower authorities with inspection, audit, and corrective powers (Recitals 39-40, Art. 21) and apply penalties (Art. 22), whilst the Annex of the Directive confirms enforcement extends beyond critical infrastructure and linked organizations.

Results from the interviews marked that in the water sector one of the main strategies for enhancing resilience involves focusing on aggregation of smaller companies. This approach reflects market-based responses to demonstrated vulnerabilities, particularly those revealed during the COVID-19 pandemic, which highlighted the critical importance of business continuity planning, risk management, and stakeholder coordination, where larger companies are referred to as more capable of maintaining their operational capacity. The CER Directive (2022) stresses SME's support as a factor of technological robustness and service continuity.

5.3. Wider impact of technological solution implementation on service delivery for the economy and society

Upon the results of the analysis, the technological solutions contribute, from an economic perspective to regional development by enhancing reliability and the resilience of infrastructure, thereby reducing economic losses from service disruptions and creating more predictable business operations. This stability catalyzes growth in related industries, such as tourism and irrigation. Meanwhile, the technological transformation generates internal benefits by shifting employees' roles from low-value maintenance tasks to higher-value activities. Improved operational efficiency, faster anomaly detection, and optimized resource allocation result in cost savings and increased competitiveness for utilities operating these CI systems.

From a social perspective, the results suggest that RII and DPM technological solutions promote equity and well-being by improving access to essential services. However, implementation raises ethical considerations. Most survey respondents identified concerns, including model bias, privacy invasion from monitoring technologies, and data security vulnerabilities. To maintain public trust, these challenges necessitate robust data protection measures, transparent communication, and GDPR compliance. According to policy documents like UNDRR's Principle 5, trust, transparency, and accountable data governance are essential for public acceptance (Principles of Resilient Infrastructure, 2022). Addressing these issues is critical to ensure that innovation supports resilient infrastructure and benefits society equitably. The CER Directive (2022) stresses that introducing new technological solutions raises ethical concerns relevant to the introduction of new technological solutions in the water and energy sectors. Recital 6 emphasizes that reliability and trust are essential for internal market functioning, highlighting risks from divergent Member State rules. Recital 32 addresses access rights misuse, requiring background checks whilst ensuring data protection compliance, balancing security with privacy. Articles 15 and 16 oblige entities to report incidents with safeguards for sensitive information and encourage transparent standards adoption. Together, these provisions reveal the ethical dimensions of deploying new technological solutions in critical sectors, where data bias, privacy, and protective measures intersect with the need for accountability. The CER Directive emphasizes that safeguarding resilience is not only a technical requirement but also a question of maintaining public confidence.

Interview results suggested the potential value of established impact evaluation procedures. Policy documents like UNDRR Principles for Resilient Infrastructure (2022) call for integrated impact assessments that combine environmental, social, and governance dimensions. They embed sustainability metrics, strengthen stakeholder engagement, and promote shared responsibility through collaborative governance. These principles align with the SDGs and Sendai Framework to ensure resilient, sustainable, and inclusive infrastructure development. The CER Directive (2022) requires Member States and critical entities to conduct integrated risk assessments every four years, addressing cross-sectoral, climate, and societal risks. It embeds sustainability metrics through resilience measures, including disaster risk reduction, climate adaptation, and stakeholder engagement via national strategies.

Regarding CI resilience responsibility, analysis results show that disaster response ability to enhance resilience and sustainability depends on well-developed contingency plans and clear sector prioritization algorithms. Utilities focus on priority sectors, specifically hospitals. In Policy documents, the UNDRR Principles (2022) stress the need to prioritize critical services through clear resilience frameworks and Net Resilience Gain commitment, highlighting contingency planning with emergency management, stress testing, and safe-to-fail designs for multi-hazard continuity. The CER Directive (2022) requires Member States and critical entities to ensure the uninterrupted provision of essential services through clear prioritization frameworks and robust contingency planning. National strategies must address cross-sectoral dependencies, whilst entities must assess risks, prioritize vital services and prepare resilience plans with business continuity and recovery measures.

CI sustainability has significant public value. Results of the interviews indicate public participation is incorporated into payment structures for adopting the new technological solutions. Varied funding mechanisms for technological solution implementation, from public support to EU grants and tariff-based financing, reflect recognition that technological advancement is a core business necessity requiring sustained investment. Policy documents like the UNDRR Principles (2022) stress that resilient infrastructure depends on diverse funding sources, including public support, EU grants, subsidies, and tariffs. The document states that collaborative financing models and public–private partnerships ensure steady investment in technological upgrades and innovation, requiring continuous and shared investment across sectors. The CER Directive (2022) confirms that resilience and technological progress require continuous investment supported by diverse funding sources. Member States are mandated to provide guidance, training, and financial resources, while the European Commission informs them of EU-level funding opportunities such as Horizon Europe and the Internal Security Fund.

The scientific literature (Paniagua & Rayamajhee, 2024; Schauer et al., 2018) highlights the importance of looking at indirect externalities' varying scales and cascading effects that reveal the complexity of the regulatory environment. The interaction of various actors in the energy and water sector requires accounting not only for external effects in respect to "market-based" transactions but also includes, besides the market and government, other organizations like voluntary associations (Paniagua & Rayamajhee, 2024). The responsibility of "internalization" of external effects and "responsibility of costs" of essential service interruption in case of disaster should be seen in a broader context of the negotiations between various organizations and resolving issues related to market- and nonmarket-based interactions. This concerns the security of production and supply in relation to indirect, spillover, and cascading effects on the whole economy and society, including not only the economic performance but also issues such as general well-being, security, and health outcomes of the population.

6. Conclusions: Enhancing the resilience and sustainability of CIs

This section draws conclusions from the results of the analysis of interviews, surveys, and policy documents. It highlights key insights in relation to the research questions.

This analysis has demonstrated that innovative technologies present significant opportunities for enhancing CI resilience, though their successful deployment requires consideration of implementation challenges and systemic barriers. The evidence presented in this article underscores the transformative potential of novel technologies, highlighting the complex interplay between innovative technologies, financial factors, and governance frameworks. Technological solutions such as Demand Prediction and Management (DPM) and Remote Physical Infrastructure inspection (RII) can significantly enhance security of supply and operational resilience, but their integration into existing infrastructure networks is not guaranteed without policy, financing strategies, and institutional frameworks.

Financing these technological solutions remains a critical challenge, as implementation, usage, and upgrading costs must be incorporated into long-, medium-, and short-term planning frameworks. While these innovative technologies often require significant upfront investment, their benefits extend well beyond operational efficiency to include broader societal gains, such as enhanced public safety, environmental protection, and economic stability. Ensuring that these benefits are integrated into the impact assessments, clear sustainability metrics, and meaningful stakeholder engagement throughout the decision-making process is required.

Overall, future proofing of CIs requires an integrated, inclusive, and forward-looking approach to resilience that balances policy, practice, and innovation, while ensuring equitable distribution of risks and rewards. Rather than pursuing fragmented, technology-centric solutions, success depends on comprehensive frameworks that address technical performance, financial sustainability, and governance effectiveness. Given the complexity of building resilient infrastructures, they must operate as adaptive systems capable of evolving with changing conditions, maintaining essential service continuity, and protecting vulnerable populations. Addressing these challenges calls for broad policy reforms across multiple dimensions.

Based on the regulatory and empirical evidence examined, several priorities are essential for advancing resilience and long-term sustainability: (1) integrating broader operational and ethical considerations into CI governance, including data privacy and trust-building; (2) strengthening policy alignment and coordination across EU, national, regional, and municipal levels; (3) modernizing regulatory frameworks, particularly for water reuse and technology licensing; (4) ensuring diversified and sustainable financing models; (5) reinforcing pre-implementation testing and structured mechanisms for knowledge sharing; and (6) institutionalizing transparent stakeholder engagement and accountability mechanisms.

As technological, environmental, and geopolitical risks continue to evolve, forward-looking evidence-based policies are indispensable to ensure adaptability, robustness, and coherence across CI sectors. Incorporating these priorities into future strategies will ensure that CIs are not only resilient to disruption but also drivers of sustainable societal benefits.

Public benefits from the sustainability of CIs and the necessity of strengthening resilience require diverse funding sources, including public support, EU grants (or similar schemes), subsidies, and tariffs, in addition to well-prepared contingency plans in case of disaster. Considering that the security of supply and resilience depend non only on direct, but on indirect spillover and cascading effects to whole economy and society, the “responsibility of costs” of essential service interruption in case of disaster should include collective actions of various institutions including public-private and cross-border collaborations.

Glossary

- Public Good: Refers to the classification of economic goods according to the criteria: "rivalry in consumption" and "excludability from consumption". Pure public goods are non-rival in consumption and non-excludable by the price. Examples are open-access public roads with no congestion or electricity infrastructure below peak demand. Common-pool resources are non-excludable, but rivalrous in consumption (e.g., drinking water, electricity infrastructure under peak load demand), while club or toll goods (e.g., toll public roads) are non-rival, but accessible only to customers who pay an access price for using the services. Private goods are rival in consumption and excludable.
- Externalities: Refer to negative and positive external effects on third parties. The related costs or benefits are normally not included in the transaction price. There are also externalities based on nonmarket social interaction, which is important to capture the size and scale of external effects on the economy and society.
- Cascading effects: Refer to effects in one sector/area that generate a chain of further effects in other domains.
- Economic Impact: Refers to the effects that actions, initiatives, or intervention have on the economy of a specific sector, region, or country. It involves changes in economic indicators such as employment levels, income distribution, GDP, business revenues, investment, and overall economic growth resulting from the implementation of the aforementioned factors.
- Environmental Impact: Refers to the effects that actions, initiatives, or interventions have on the natural environment. It encompasses changes, disturbances, or disruptions to ecosystems, biodiversity, natural resources, and environmental quality resulting from these actions. Environmental impact is related to an (economic) activity or product, including any emissions of polluting and toxic substances that are harmful to the natural and human environment, also including use of mineral resources, water and other natural resources that are renewable as well as non-renewable.
- Impact Assessment Area: Refers to a specific impact evaluation field, such as social, environmental, economic or scientific.
- Impact Assessment: A process used to evaluate the potential effects or consequences of a proposed action, policy, program, or project on various aspects such as social, economic, and environmental factors.
- Social Impact: Refers to the effect that actions, initiatives, or interventions have on society and community in which it operates. It encompasses the changes, improvements, or consequences that occur within social structures, relationships, behaviors, and well-being of individuals or groups as a result of these actions.
- Sustainability Roadmap: Refers to a strategic plan that outlines how the project's impacts will continue beyond the official project end data.

Supplementary material:

A. Interview guideline
B. Excerpt from the questionnaire: Demand Prediction and Management (DPM) solution
C. Excerpt from the questionnaire: Remote Physical Infrastructure Inspection (RII) solution

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Data statement
In compliance with Research Ethics Committee requirements and applicable data protection legislation, the research data are not publicly available. Participants in interviews and surveys did not provide consent for data sharing or for secondary analyses beyond the scope of the approved research protocol.

Ethics of Human Subject Participation
This study was conducted in accordance with the General Data Protection Regulation (GDPR) (EU 2016/679), and all procedures involving research participants were approved by the Ethics Committee for Research of the Luxembourg Institute of Socio-Economic Research (Ref: REC/2024/089.SUNRISE/2). All participants in the survey and interviews provided written consent. They were informed about the data management procedures and given the opportunity to object to the use of their data.

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Declaration of interests
☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the writing process
During the preparation of this work the author(s) used AI-based Software *aTrain*, licensors Armin Haberl, Jürgen Fleiß, Dominik Kowald, Stefan Thalmann (cf. Haberl, A., Fleiß, J., Kowald, D., Thalmann, S., 2024. "Take the aTrain. Introducing an Interface for the Accesible Transcription of Interviews.", Journal of Behavioral and Experimental Finance 41. https://doi.org/10.1016/j.jbef.2024.100891) in order to transcribe the audio text of the interviews conducted for the preparation of this article. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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