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Smart Infrastructure

Italian infrastructure between challenges and innovation

2025

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TIM Research Centre

With the contribution of INTESA SANPAOLO INNOVATION CENTER S.P.A.
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Introduction

Roads and bridges. Aqueducts and sewers. Roman civilisation advanced through a dense network of infrastructure that has spanned the centuries, leaving the world a testimony of its greatness, alongside other ancient Asian and American civilisations.

Nearly two millennia later, driven by steam power and the discoveries of the nineteenth century, a new wave of infrastructural development brought railways, pipelines, power and telecommunication networks, which enhanced progress and economic growth.

Networks then became wireless, using radio signals transmitted through the air. This shift enabled radio and tv, voice and data to enter our households. Mobile networks later carried the digital revolution across the globe.

Today's infrastructures are evolving into smart and sustainable networks, becoming more efficient, reducing waste, minimising risks, and ensuring greater resilience. This is why they overlap, and in some cases, integrate with one other, blurring the boundaries between them. It is a silent yet radical transformation: bridges, ports and railway lines may look the same, but their very nature is changing, projecting them into a parallel infrastructure dimension.

Take a dam. Traditionally, it is a solid structure built to block a watercourse, regulate its flow and create a reservoir. But today, it is much more than that: it generates hydropower, hosts floating photovoltaic implants, supplies water for hydrogen production, and cools data centres. It can transform rivers into navigable waterways, support roads along its crest and house 5G antennas for advanced connectivity. Through its sensors, the dam becomes a living system who listens, measures and reacts. It functions like an environmental monitor, detecting vibrations, pressure variations and weather conditions, enabling remote monitoring, enhanced security and predictive maintenance. The dam is therefore no longer just a simple barrage: it becomes a keystone connecting water, power, transport, telecommunication and digital networks, gaining new capabilities through technologies that expand its value and make it more functional. Data availability, processing power, connection speed and the synergy between drones and sensors are transforming individual networks into smart and interconnected ecosystems. These communicate with one another and create dynamic environments in which every node becomes part of a larger system able to operate beyond its original function and turn complexity into shared opportunities for sustainable growth.

This transformation inevitably affects a country's entire infrastructural system, which must be reconsidered and redesigned with a new perspective to adapt to a context that is constantly evolving and presenting constant challenges. In today's complex geopolitical landscape, the goals of growth and sustainability are joined by that of resilience, as such a pervasive and essential system must be able to withstand the increasing risks of our time.

The current report, prepared by TIM Research Centre in cooperation with Intesa Sanpaolo Innovation Center, Digital Innovation Observatories of the Politecnico di Milano and Comtel Innovation – Centro Studi and Insight, examines the transformation of the Country's strategic networks, with particular attention to civil, water and energy infrastructures. The robust Recovery and Resilience plan launched to revitalise European economies after the pandemic containment measures, has given new momentum to infrastructure investments in both Europe and Italy.

Specifically, this report focuses on the digital monitoring of infrastructure, an essential element for making assets and network nodes truly smart and a strategic lever for the country's security, efficiency and sustainable growth. Beginning with an assessment of Italy's infrastructure assets, the report outlines the main technological developments shaping these sectors and provides a market sizing of digital network monitoring solutions. It then compares Italy's ongoing development plans with the transformation processes under way in other major European countries, highlighting a shared trajectory toward more secure, efficient and sustainable infrastructure driven by digital technologies. The report quantifies the potential benefits of this evolution – lower costs, economic development, greater sustainability and enhanced resilience – using a series of practical examples.

Today's infrastructure transformation goes far beyond a simple technological upgrade. It is a deeper and more complex shift that shapes a Country's development strategies, competitiveness and social cohesion. We now have the opportunities, technologies and resources to build future-proof infrastructural systems and networks that will help future generations meet the economic, environmental and social challenges of tomorrow. We must have the courage to turn this opportunity into real change.

Part One

Infrastructures

CHAPTER 1: Civil Infrastructure

The relevance of civil infrastructure

Infrastructure provides essential services for the proper functioning of the economy: roads, railways, ports, schools, hospitals, and so on. Their importance is evident when considering that, in industrialised Countries, they account for 35-40% of total assets, forming one of the four major areas of the construction sector, alongside building constructions, restoration and plant systems. For an appropriate classification, it is necessary to analyse both the function of the various structures within the infrastructural system and their distinctive features[1]. Among the classifications found in the literature, the one proposed by D. Biehl[2] in a 1991 study is particularly significant from the perspective of digitalisation and it distinguishes between:

• Network infrastructure

These include all systems spread across the territory and characterised by inter-connected nodes. To be efficient, they must reach wide geographical areas or a large number of users.

Examples:
road and rail transport networks, communication networks, electricity, gas and water distribution systems, waterways and soil protection works.

• Punctual infrastructure

These are structures characterised by high immobility, indivisibility, irreplace-ability and multifunctionality.

Examples:
hospitals, schools, museums, alongside basic infrastructure such as prisons, police and army stations, courts.

According to Biehl[3], infrastructure plays a key role in the development of a geographic area, which can be measured in terms of income, productivity and employment:

> ***«A region well equipped with infrastructure has a competitive advantage over a less equipped one, resulting in higher per capita GDP and/or higher employment levels. Consequently, regional productivity, income and employment grow as infrastructure assets increase».*** (Biehl, 1991).

Besides, infrastructure is one of the regional development factors that policy makers can directly influence, underscoring the importance of measuring their actual presence across the territory[4].

Civil infrastructures with high socioeconomic impact: transport networks

Transport infrastructure is among those that directly support production, along with energy and gas distribution networks, water collection and distribution networks, sewage and telecommunication networks (including broadband and Internet connectivity). They are designed to improve the mobility of people and goods and promote socioeconomic development and territorial competitiveness. Three main typologies are identified:

- Road infrastructures: urban/suburban roads and motorways.
- Railway infrastructures: national, regional and metropolitan networks.
- Airport infrastructures: airports and ports for maritime transport.

The report published by ANSFISA – the National Agency for the Safety of Railway, Road and Motorway Infrastructure – is a useful reference to quantifying railway and road infrastructure in Italy.

According to the latest findings, the Country has over 840,000 km of road network, over 60,000 bridges and more than 2,200 tunnels[5]. Within the European Union, Italy has the highest number of road and railway tunnels.

Besides, national and regional railway networks extend for approx. 18,900 km, with 5,443 railway crossings, 288 stations and 225 km of mass rapid transit lines (undergrounds), of which 131.6 km in tunnel[6].

A large infrastructure heritage

within the European Union, Italy has the highest number of road and railway tunnels.

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The infrastructure asset to be managed is therefore extremely large, involving more than 8,000 entities, including supervisors and service providers. Of Italy's 840,000 km of road networks, just over 35,000 km (about 4%) are trunk roads and motorways, around 80% of which is managed by Municipalities through their 7,904 supervisory bodies. There are also 123 provincial, regional and metropolitan road authorities responsible for a further 16% of the network. In short, more than 96% of Italian roads are managed by local authorities, while the remaining 4% falls under national entities such as Anas S.p.A. (Gruppo FS Italiane) and motorway concession companies[7].

Excessive management fragmentation

over 8,000 subjects between supervisors and companies

According to the UPI report dated 27/08/2018, the Provinces of the Ordinary Statute Regions (excluding metropolitan cities) manage around 100,000 km of roads and at least 30,000 infrastructures, including bridges, viaducts and tunnels[8]. The maintenance of the national non-toll road and motorway network is entrusted to Anas S.p.A. through a concession and agreement with the Ministry for Infrastructure and Transport (2002). Currently, Anas manages more than 32,000 km of roads and motorways, 18,720 bridges and viaducts and 2,157 tunnels[9]. Conversely, more than 8,000 km are managed by motorway concessionaries, of which 4,187 km belong to the TEN-T (Trans-European Transport Network). However, the condition of these assets is fully known for only 10% of them[10].

A first assessment by ANSFISA covering around 800,000 km of road network (including regions, provinces, metropolitan cities and municipalities) revealed incomplete and often lacking data. Multiple layers of regulation, frequent changes in management and the age or the works make it difficult to obtain consistent information on the network and its features. The latest surveys on the municipal road system date back to 1999, indicating around 668,000 km of municipal roads and more than 135,000 km of provincial and regional roads. Qualitative data, also essential to developing modern Security Management Systems, is still lacking. To address this, ANSFISA started a survey involving local authorities to gather information on the relevant networks[11].

Under the Traffic Code, the relevant bodies are responsible for the maintenance, management and cleaning of roads and their associated areas, as well as for road signage and technical efficiency checks. In general, infrastructure safety falls under the responsibility of its supervisory body[12].

An incomplete and defective knowledge.

Multiple layers of regulation, frequent changes in management and the age of the works make it difficult to obtain consistent information.

Maintenance and safety of transport infrastructure: ANSFISA and AINOP

Over time and with regular use, infrastructures undergo natural wear that, if not properly managed, leads to deterioration of the assets, with negative impact on the economy, users' safety, service efficiency and increasingly higher reconstruction costs. The primary objective of maintenance is to preserve the asset over time. Civil Infrastructures – roads, bridges, tunnels – that make up the transport network for people, goods and services (waterworks, pipelines, power lines, telecommunication networks) were built over a period of 70-90 years. A study conducted by the Politecnico di Milano a few years ago estimated that in Italy there were at least 1,900 bridges with "very high structural risks"[13], over the 61,000 existing nationwide.

High risk of deterioration

In 2021, at least 1,900 bridges showed "very high structural risks", over the 61,000 existing nationwide.

The main challenges arise from the high number of variables: materials, dimensions, construction period, lack of detailed information on many works and the difficulty of defining consistent assessment and management criteria. Added to this is the lack of financial resources and qualified staff to carry out surveys and in-depth inspections across the entire infrastructural park. The managing bodies must operate with limited budgets, keeping the works in service without interruption, starting with a preliminary assessment on the current state and then planning and carrying out the necessary interventions.

In recent years, the need to invest in maintenance knowledge and resources has increased, driven both by greater awareness on the infrastructure condition and by regulatory developments, unfortunately prompted by a serious tragedy. The collapse of the Morandi bridge led to the adoption of maintenance and design practices that have long been technically possible but had not yet been implemented. In the aftermath of the collapse, the so-called Genoa Decree was approved and published in the Official Journal on 19 November 2018. Although not a construction regulation, the Decree represents an important milestone in Italy's approach for the protection of major works. It contains provisions on the structural monitoring of public infrastructure, introducing 5G technology and more innovative tools. The Ministry is required to adopt extraordinary plans for the most critical structures, setting priorities based on territorial hazards and vulnerabilities.

Turning point after the Morandi bridge tragedy

Italy accelerates monitoring and innovation, establishing ANSFISA and AINOP to protect major public works.

To manage this process consistently, ANSFISA[14] (art.12) was established, with the additional task of drawing up a national plan for the upgrading and development of road and motorway infrastructure, in order to ensure its safety.

Operational since 30 November 2020, ANSFISA took over ANSF (Agenzia per la Sicurezza delle Ferrovie), transferring its railway know-how to the road, motorway and rapid mass transit sectors[15]. Its task is to monitor the safety conditions of infrastructure. The agency, supported by ANCI (Associazione Nazionale Comuni Italiani) and UPI (Union Province Italiane), is promoting the adoption of management, monitoring and control systems, guiding supervisory bodies – especially those with fewer resources – in the implementation of efficient Safety Management Systems[16].

ANSFISA's objectives are to raise terrestrial infrastructure safety standards, to certify and plan maintenance interventions, and to digitalise and enhance verification processes, supporting the adoption of preventive maintenance strategies. To implement this approach, a compete mapping of the assets is essential, based on reliable and consistent classification criteria.

Safety of Italian roads: the findings of the first report by ANSFISA

The establishment of ANSFISA has provided a first snapshot of the state of health of the Italian road and railway infrastructure. According to the 2020 report, 90% of the motorway network had a certified management system. Among the most widespread certifications:

- ISO 9001 – Quality management
- ISO 14001 – Environmental management
- ISO/IEC 27001 – Information security management
- ISO 45001 – Occupational health and safety management
- UNI ISO 39001 – Road traffic safety management

Norm ISO 39001 defines the international standard for road traffic safety, including risk management and regulatory compliance. The adoption of a certified ISO 39001 Road Traffic Management System contributes to the reduction of serious accidents.

The system allows the constant monitoring of related activities and processes, with the aim of prevention, control and constant improvement. It is intended for transport, road maintenance, logistics and companies' fleet.

Alongside ANSFISA, the Ministry for Infrastructure and Transport established a national digital archive for public works (AINOP[17]) through law no. 130 of 16 November 2018 and D.M. no. 430 of 8 October 2019. The AINOP has to catalogue all public works assets under the jurisdiction of the State, regional and local bodies, autonomous provinces, metropolitan cities and municipalities, assigning each public work a unique code. The code conveys information on technical data, condition and degree of efficiency, ordinary maintenance activities and the current state of play.

AINOP is managed through a digital platform that enables the identification of each work and its territorial location[18], provides technical monitoring tools, prevents critical issues and activates smart warning systems. It also make it possible to display a "virtual file" for each work, to identify infrastructures that require safety intervention and define priorities.

Establishment of a digital archive** to catalogue and monitor Italy's public works assets, based on **reliable classification criteria

National Digital Archive of Public Works

Nine specialised sections to monitor the state of Italian civil works

AINOP is organised in 9 sections:

- Bridges, viaducts and road overpasses
- Bridges, viaducts and railway overpasses
- Roads
- National, regional and metropolitan railways
- Airports
- Dams and waterworks
- Railway and road tunnels
- Ports and port infrastructure
- Public constructions

Each section is divided into subsections that collect personal data, technical and historical information, economic and financial data, elements relating to management and safety, constant monitoring through sensors and satellite surveys, efficiency status, ordinary and extraordinary maintenance activities, photographic records and reporting.

A different model for transport infrastructure management

Road infrastructure maintenance should not be limited to emergency management and restoration but should also include risk analysis activities and preliminary assessments. The objective is to prioritise targeted interventions over indiscriminate maintenance, providing guidelines to direct large investments currently earmarked for safety and knowledge.

This is allowed by infrastructure digitalisation, integrated with monitoring systems whose cost is now negligible compared to the construction of new works.

These systems enable real-time measurements which, when properly assessed, provide supervisory bodies with useful information.

From emergency management to preliminary assessment.

Targeted and timely intervention enabled by infrastructure digitalisation

More efficient and sustainable infrastructure thanks to the NRRP's European funds

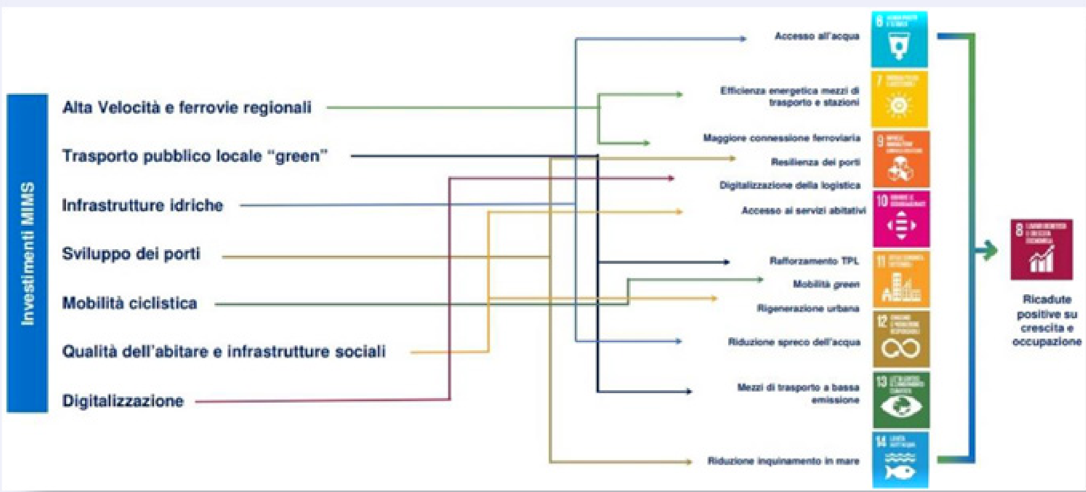
To innovate its infrastructure management system, Italy could benefit from the investments provided under Next Generation EU (NGEU), which allocates unprecedented resources to digital transition and sustainability, creating the conditions to integrated technological innovation and infrastructure governance.

Italy is the main beneficiary of the NGEU's two-key tools: the Recovery and Resilience Facility (RRF) and the REACT-EU Programme. The RRF provides 191,5 billion Euros to be used by 2026. To access these resources, on 30 April 2021 the Italian government submitted to the European Commission the National Recovery and Resilience Plan (NRRP), with projects, investments and reforms with allocation criteria and deadlines approved by the EU.

Added to these resources are the National Complementary Plan, with similar objectives but with a broader time horizon.

During the implementation of the PNRR, the Ministry of Infrastructures and Transport (MIT) is responsible for the overall management of the Plan and the allocation of resources to the implementing bodies: Regions, Autonomous Provinces, local bodies, concessionaries and other authorities or companies involved in the implementation of operations and the modernisation of the transport system for a sustainable development, to meet the Sustainable Development Goals of the 2030 Agenda.

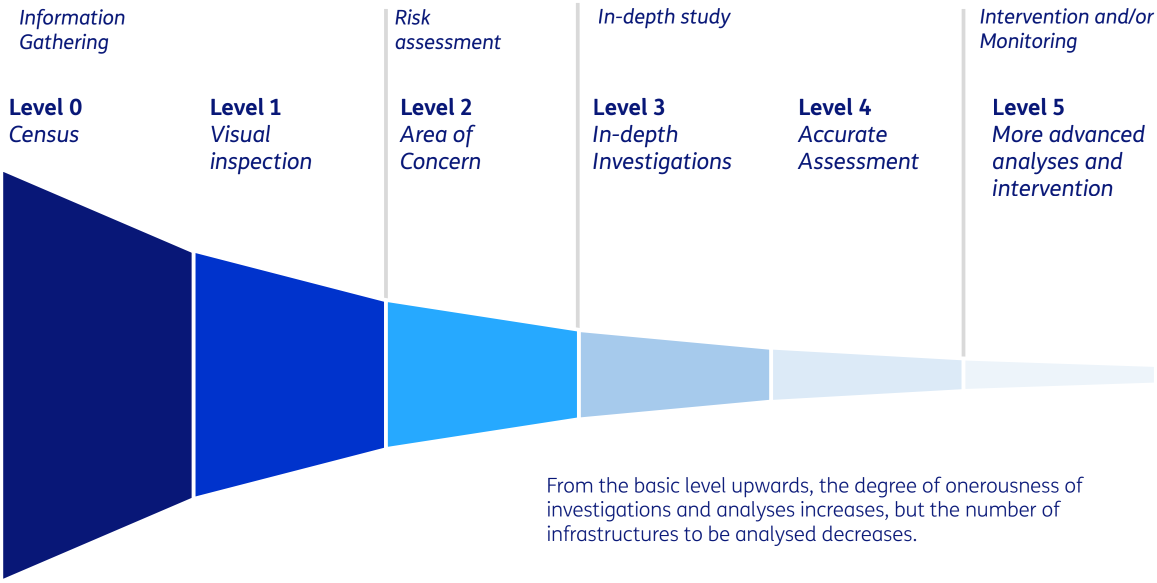
Investment analysis by the MIT relating to the goals of the 2030 Agenda



Source: MIT- Ministry of Infrastructures and Transport

Managing and maintenance of bridges and viaducts

In 2020 the Higher Council of Public Works issued Guidelines for classification and risk management, safety assessment and monitoring of existing bridges[19] and viaducts. Their objective is to ensure that these infrastructures are monitored and maintained in safe conditions through three main activities: cataloguing and risk classification, safety assessment and continuous monitoring. In Italy the number of bridges is very high and their features are complex, consequently a multilevel approach has been adopted. Through the gathering of basic information, it calculates the Area of Concern (AoC) of each work and identifies the appropriate level of control, based on the challenge detected. Finally, the last chapter of the Guidelines translates the different levels and AoC results in real surveillance, monitoring and maintenance actions, ensuring a continuous and targeted approach to bridge safety (see box).



The area of concern (AoC) is the hearth of the system: each bridge is placed in one of the five categories, from the highest to the lowest, in order of priority:

High Area;
Medium–High Area;
Medium Area;
Medium–Low Area;
Low Area.

The relevant risk categories are structural and foundational, seismic, landslides and hydraulic; to each, an AoC is associated. For each risk typology, primary and secondary factors are identified, and the following are calculated: vulnerability, hazardousness and exposure.
High-area bridges require immediate intervention, detailed structural models and ongoing monitoring systems to prevent situations of risk.
Intermediate classes require regular checks, non-routine inspections in case of deterioration and, if necessary, in-depth studies.
For the lowest classes, instead, regular inspections without further analyses are sufficient.

From risk assessment to risk management

The Guidelines also include the procedure's minimum indications, criteria and requirements to plan and carry out structural safety management activities of existing bridges.

Management activities cover four main areas: surveillance, control, inspection and monitoring.

Routine inspections and structural monitoring help to assess the condition of the work by estimating both the current state of damage and how damage may evolve over time through predictive analyses. The surveillance and monitoring systems operate according to a "risk-based" strategy, which depend on the bridge's relevant Area of Concern.

It may include:

- routine or non-routine inspections;
- non-destructive and semi-destructive surveys;
- static loading tests and surveys of dynamic responses;
- instrumental monitoring;
- analysis algorithms and interpretation of data;
- representative models of real behaviour;
- indicators of the state of condition and deterioration models;
- IT databasex.

Routine inspections

are carried out with a minimum frequency based on the Area of Concern of the bridge and the history of inspections. They vary depending on whether the structure is already part of a surveillance system or is a new or long-standing bridge which has never undergone routine inspections. They are mainly carried out visually, supported by tools that allows defects to be identified, also through photographs and digital platforms. When using drones or robotic equipment, the data must be geo-localised and specifically referred to the element being analysed.

Non-routine inspections

to further investigate the deterioration already detected. To be carried out within 60 days from the reporting of an evolving damage, or within maximum intervals of 5 years for the less challenging works and 2 years for the most relevant ones. They must be documented and uploaded to the managing platforms. In some cases, during the non-routine inspections, loading tests and dynamic analyses can be carried out, to compare real data with theoretical models, update the parameters and interpret any anomalies. The results are recorded in dedicated files.

Structural Health Monitoring

is to detect any damage at an early stage, via sensor networks and hardware/software systems which record parameters such as strains and accelerations, automatically processing them to ensure timely interventions and improve the safety of the infrastructure.

Managing and maintenance of tunnels

In 2022, the Higher Council of Public Works issued similar Guidelines to the ones already established for bridges[20], for the classification and risk management of existing tunnels[21]. These Guidelines complement other road and fire safety regulations and apply to road tunnels with length of 200 meters or more, including fornixes, artificial tunnels, rockfall barriers and underpasses. For shorter works, application is assessed on a case-by-case basis, particularly where hydraulic challenges are present. The management of international tunnels is entrusted to intergovernmental Commissions.

The main objective is to standardise methodologies for intervention, planning and classification. Likewise, these Guidelines establish a multicriteria, multilevel approach, that transforms infrastructure management. The process begins with cataloguing and preliminary assessments to assign each work an area of concern, from which more in-depth analyses are developed, using innovative technologies such as drones, sensors, optical fibres and artificial intelligence (AI) systems.

The process is similar to the one already described for bridges and viaducts, using a system based on six progressive levels and four areas of concern (low, medium-low, medium-high and high). The differences obviously relate to the specific features of these works compared with bridges and viaducts. For example, regarding tunnels, geomorphological and hydrogeological features play a greater role, starting from the inspection phase. Within the Areas of Concern, specific risk factors are assessed, including the condition of lighting, ventilation and firefighting systems, as well as any local damage and interactions with natural formations.

Come si gestivano le gallerie prima del 2022

Un percorso tra le regole e le prime azioni di manutenzione preventiva

Prima del 2022, chi si occupava delle gallerie seguiva diverse regole, basate su leggi generali come le NTC 2018, il Nuovo Codice della Strada (D.Lgs 30.04.1992 n. 285) e altri regolamenti tecnici legati alla costruzione e manutenzione delle strade.

Queste leggi includevano anche norme sui contratti pubblici e aggiornamenti fino al 2021.

Il primo passo importante verso una manutenzione programmata risale al 19 luglio 1967, dopo il crollo del ponte di Ariccia. In quella data, il Ministero dei Lavori Pubblici ha emesso una circolare con le regole per controllare la stabilità delle strutture stradali, indicando quando e come fare le ispezioni e promuovendo così la manutenzione preventiva come una pratica fondamentale.

Monitoring is often more complex and requires special attention to smoke and temperature detection, along with periodic inspections of internal spaces.

Safety must be addressed at local level, defining priorities based on the risks of individual works and on network resilience. The assessment on any intervention also considers the socio-economic impact of potential disruptions. Following exceptional events (shocks, fires, seisms) non-routine inspections are planned. The tunnel Supervisor, supported by experts and inspectors, oversees the entire activities programme – from data cataloguing to surveys and monitoring planning – and records everything in in the complementary document to the maintenance plan.

Smart Infrastructure Monitoring: Origins, Evolution and Perspectives

Civil infrastructures – bridges, viaducts, tunnels – are strategic elements for a Country's mobility and safety. However, the ageing of works, increasing traffic loads and changing environmental conditions require a rethinking of maintenance strategies.

Many of these works are approaching the age of their estimated life cycle and were designed according to standards that are now outdated; as strategic structures, their collapse could result in human losses and significant social and economic consequences.

This highlights the need to control structural behaviour through digital tools that can be continuously queried, rather than through methods requiring on-site presence. In this context, smart infrastructure monitoring – also known as Structural Health Monitoring (SHM) – is born, representing a revolution in the management and preservation of major works. SHM is explicitly referenced in the 2020 and 2022 guidelines.

Structural Health Monitoring (SHM): *a revolution on how to manage and preserve major works*

The notion of structural monitoring emerged in the 1980s and 1990s as a response to the increasing need to quantitatively assess infrastructure conditions. Initially, SHM was considered an applied research topic, with trials limited to pilot projects and structures of recognised scientific relevance[22].

The initial applications concerned bridges and dams, with systems based on wired sensors and manual acquisitions. The aim was to verify design hypotheses and reduce the risk of sudden collapses. However, system complexity and high costs limited their uptake.

In the years 2000s, owing to advances in sensor and communication technologies, SHM began evolving towards more practical and scalable solutions. The introduction of wireless networks, fibre sensors and distributed systems reduced installation and maintenance costs, facilitating large-scale adoption[23].

Smart infrastructure monitoring is an integrated system that uses permanent sensors, data transmission networks and analysis algorithms to assess a structures' state of health in real time. Unlike traditional visual inspections, often subjective and costly, SHM provides continuous and objective measurements of physical quantities such as vibrations, displacements, tensions and environmental variables (temperature, humidity, wind)[24].

The relevant data is processed using data-driven approaches and, in some cases, predictive models to identify anomalies, estimate residual life cycle and plan targeted interventions[25]. The goal is to shift from reactive to predictive maintenance, reducing costs and increasing safety.

The idea behind structural monitoring is to develop autonomous systems capable of continuously monitoring works, enabling remote inspections and the immediate detection of any damage with minimal human intervention. It is both about identifying damage when it occurs, and understanding how it evolves, estimating the structure's remaining useful life and planning maintenance interventions to extend its life cycle.

Structural Health Monitoring (SHM) systems are rapidly spreading: more and more often, new infrastructure is designed with integrated sensors and digital technologies, turning bridges into true "smart organisms". Due to the combination of digital vision, advanced sensors, smart cameras and artificial-intelligence algorithms, it is possible to analyse structural behaviour in real time and prevent deterioration phenomena. By continuously processing the collected data, these systems can send immediate alerts to providers, enabling targeted and timely interventions.

Structural monitoring is not limited to new or existing works but can be applied in a wide range of scenarios: from monitoring structures affected by nearby construction or demolition works, to assessing long-term displacements and material fatigue phenomena. It can be used to verify integrity after seismic events, analyse deterioration processes for construction and maintenance planning, and provide feedback cycles that are useful for improving future design. In this way, a performance-based approach is promoted, oriented towards infrastructure safety and durability. Structural monitoring may vary depending on several parameters (timing, scale, modes, technologies) and is therefore an adaptable approach suitable for different contexts.

Category	Subtype	Description	Key features	Examples
TIME FRAME based on monitoring timing	SHORT TERM	Temporary monitoring with sensors that remain active for short periods. It is used to obtain punctual information or follow specific interventions.	Targeted interventions, short duration, quantity of acquired data limited	Demolitions, redevelopment works
	LONG TERM	Ongoing systems for prolonged analyses. Indicated for slow deterioration or to study overall behaviours.	Large amount of acquired data, use of sophisticated detection tools	Crack formation, settlement of foundations
EXTENSION defining if the monitoring concerns whole structures or single elements	GLOBAL	Analysis of the whole structure.	Overall behaviour	Vibrations
	LOCAL	Observation of damage on single elements.	Focus on critical elements	Crack propagation, span strain
MODALITY It is referred to frequency and type of phenomena observed	STATIC	Parameters changing slowly (temperature, humidity, displacements).	Slow and regular measurements.	Tracking every hour
	DYNAMIC	Rapid phenomena (vibrations). Two strategies can be used: measurements at regular intervals (12-24 hours) with high frequencies (around 200 Hz) to define a model of behaviour or measurements activated if thresholds are exceeded (trigger).	Dynamic evolution analysis, anomalies detection.	Vibrations from traffic, passage of heavy vehicles
STRUCTURAL MONITORING TECHNOLOGIES depending on technological solutions	WIRED	Cable communication (wires, coaxial, optical fibres). Advantages: high band, higher reliability. Disadvantages: high costs, complexity.	Sophisticated methods (vibrations, data merging).	Williamsburg Bridge, Manhattan Bridge
	WIRELESS	Wireless communication. Advantages: easy installation, reduced costs. Disadvantages: limited band, signal loss.	Easy maintenance, IoT and 5G integration.	Accelerometers, inclinometers

In particular, the technologies used for detection play a key role.

Wired structural monitoring systems offer several advantages: they enable long-distance data transmission without signal loss, operational rapidity and large bandwidth capacity. They can also integrate advanced devices, such as fibre and smart sensors, to detect structural conditions. This reduces the risk of data loss and supports sophisticated analysis methods, including vibration-based techniques, data fusion and impedance. In recent years, the use of advanced sensors in cabled systems has increased significantly. However, these systems are more expensive than wireless solutions, as they require a complex network of cables and connectors. Moreover, cables can be damaged during construction, leading to higher maintenance and repairing costs. In the United States, cabled monitoring systems have been installed on several major bridges, including Williamsburg Bridge, Saint Anthony Falls Bridge and Manhattan Bridge.

Wireless structural monitoring systems use wireless technologies to connect sensors and collect real-time data. These sensors are often autonomous and can be integrated with legacy devices such as accelerometers and inclinometers. Wireless systems offer significant advantages: easy installation, lower costs and greater flexibility. By eliminating cables, maintenance becomes simpler and adding or relocating sensors is much easier. Moreover, these systems are highly integrated and require few supporting components, which reduce overall complexity. Wireless system drawbacks are related to limited bandwidth, potential signal loss and power supply challenges. However, the integration of advanced technologies such as IoT and 5G with growing R&D activities is helping to overcome these limitations. The evolution towards more efficient and reliable wireless networks is expected to promote an increasingly widespread adoption of these solutions in structural monitoring.

Technological changes in civil infrastructure management

Technology evolution: the three key factors of SHM

In recent years, the evolution of SHM has been driven by three main factors:

- the development of advanced sensors: from traditional extensometers and accelerometers to optical-fibre devices capable of measuring strains and temperatures along the entire structure. These sensors offer high precision and strong resistance to environmental conditions, making them ideal for bridges and tunnels[26].
- Pervasiveness of wireless communication networks. Wireless networks have removed the complexity of cabling, enabling the creation of auto-organised, scalable and resilient systems. This has made it possible to integrate sensors that measure environmental and operational variables, reducing false alarms and improving the accuracy of analyses[27]. To better understand and systematically analyse the environment, large-scale sensor networks, composed of low-energy nodes and limited processing and memory capabilities, have increasingly been adopted. Potential valuable applications of wireless sensor networks include military security, physical sensing, traffic monitoring, industrial automation, air traffic

Reti di sensori wireless auto-organizzanti

per monitoraggio ambientale e prevenzione danni

Le reti wireless eliminano la complessità dei cablaggi e consentono la creazione di sistemi auto-organizzanti, scalabili e resilienti. Inoltre permettono di integrare sensori per variabili ambientali (es. vento, temperatura, umidità) e variabili operative (es. carichi da traffico), riducendo falsi allarmi e migliorando l'accuratezza delle analisi

Un esempio concreto è dato dall'applicazione di reti di sensori wireless collegati con IoT nel monitoraggio e la gestione delle dighe.

Le grandi dighe sono infrastrutture fondamentali, soprattutto per la produzione di energia elettrica, ma comportano anche rischi significativi. Per gestirle in modo sicuro è essenziale avere informazioni aggiornate quotidianamente sul loro stato. Nel mondo ci sono migliaia di dighe, e la loro sicurezza è cruciale: un eventuale cedimento potrebbe avere conseguenze gravissime per milioni di persone. A questo scopo è stato sviluppato un sistema informativo che sfrutta tecnologie già esistenti, integrando reti di sensori wireless (WSN) e soluzioni basate sull'Internet delle Cose (IoT). L'obiettivo è creare un sistema capace di inviare allarmi in tempo reale quando i parametri di sicurezza si discostano dai valori normali. Quindi, oltre i parametri strutturali delle dighe, anche i parametri ambientali al contorno devono essere attentamente monitorati e integrati in un sistema capace di prevedere i problemi prima che si manifestino.

In uno studio mirato allo studio di come garantire il corretto funzionamento delle apparecchiature nei tunnel delle dighe, è stata esplorata l'adozione di reti di sensori wireless per migliorare le prestazioni dei sistemi DSM basati su cavi centralizzati. Il progetto presentava una valutazione del sistema di monitoraggio della sicurezza delle dighe basato su WSN per validarne l'efficienza. Grazie alla cooperazione di diversi agenti per le applicazioni DSM, la rete di sensori wireless distribuita può allocare automaticamente i compiti, auto-organizzarsi e combinare le informazioni provenienti dai vari sensori.

control, smart buildings and monitoring of natural borders.

- Data analysis computational power and Artificial Intelligence technologies. The impossibility of developing comprehensive predictive analytical models led to the adoption of data-driven approaches based on statistical algorithms and machine learning. These systems make it possible to identify trends, anomalies and correlations among variables, supporting more informed decisions[28].

Key technologies: from acquisition to smart maintenance

Data Acquisition Systems (DAS)

Data Acquisition Systems are essential to collect information on structure condition. The main technologies used include:

- **Data loggers**, acquiring raw data from sensors for subsequent recovery. They can be programmed for specific intervals or triggers.
- These systems also include **wireless communication modules** for safe data transmission towards central servers or cloud platforms.
- **Edge computing** equipment can perform basic processing directly on the sensor, enabling real-time decisions.
- The **interface cards** in cabled systems are used to connect data loggers or sensors to computers for acquisition and processing.
- Finally, the **Field Programmable Gate Arrays** (FPGA) are versatile programmable chips to customise data acquisition and processing tasks, tailored to SHM applications.

Static sensors

Static sensors are used to continuously monitor a structure's quasi-static response to operating stresses and environmental parameters. This type of response relates to slow and gradual variations over time, such as cracking or strains, which do not require high frequency data acquisition. In fact, collecting excessive amounts of data would be unnecessary and would generate files that are too large to manage.

The sampling frequency is generally set in two ways: hourly acquisition for low-demand structures, or 1 Hz acquisition for continuous monitoring.

To facilitate understanding and data organisation, sensors are classified according to their specific features, making their function and role within the monitoring system clearer.

Most of the sensors used in monitoring works detect aspects like strains, displacements, rotations, tensions.

Some sensors, in addition to providing structure information, are also used to monitor external phenomena such as bank erosion or watercourse behaviour.

There are also sensors that detect environmental parameters which affect the concrete of the works, as well as its condition.

The pendulum is a sensor based on the plumb-line principle. It monitors rotations and displacements in large structures, such as dams, towers and bridges, detecting variations related to the gravitational vertical.

- Expected output: graphic representation of displacements or rotations detected over time.
- Quality of the acquired data: stable and not influenced by environmental factors such

as temperature and does not require post-processing.

- Data usage: in monitoring systems (BMS), data is used both at sensor level and at structural element level. In the first case, instantaneous measurements, thresholds set by the supervisory body and historical records are transmitted. In the second case, data from multiple sensors is aggregated to obtain a representative average, useful for rapid consultation. In the event of anomalies, detailed analysis of individual sensors is carried out to assess the extent of the problem. Data related to slopes is not integrated into BIM models, but it is managed separately through GIS systems.

The vibrating-wire extensometer measures structural strains by detecting changes in the frequency of a tensioned steel wire, making it ideal for use in the highest stressed points of the structures. It is applied in several structural fields, including dams, bridges, viaducts, steel structures, foundations and diaphragms. To improve measurement accuracy, sensors can be equipped with a thermistor that allows temperature effects to be corrected. Owing to its watertightness, it can be installed either on the exterior of structures or directly embedded in concrete castings.

- Expected output: graphic representation with time on the x-axis and strain on the y-axis, allowing continuous and accurate monitoring of structural behaviour over time.

Displacement transducers (LVDT) measure linear movements between nearby points and are ideal for monitoring pertaining displacements in structural elements.

- Expected output: curve showing displacement over time.
- Quality of acquired data: to obtain reliable information, signal cleaning is necessary to filter out environmental disturbances.
- Data usage: in BM Systems, data is used to assess instantaneous displacements, thresholds set by supervising bodies and historical monitoring records.

Load cells measure tension in structural elements and are used to monitor tension loads and losses in critical points of the structures.

- Expected output: tension-time curve
- Quality of the acquired data: it is necessary to clean the signal to eliminate environmental noise.
- Data usage: in BM Systems, data is used to assess instant tension, safety limits and historical records, both at sensor and structural element level.

In structural monitoring, several sensors are used to detect scour and soil erosion, in particular beneath bridge piers and abutments. Floats, magnetic collars and sonars are technologies employed to monitor erosion under bridges: the first rise to the surface and transmit wireless signals when sediment is removed, the second detect depth using magnetic triggers, while sonar measures changes in the riverbed using sound waves, each with different sensitivities and installation methods. The timed mobile rod detects erosion by measuring vertical displacement through an electrical motor and a revolution counter.

- Expected output: the measured data is represented as a function of time and depth or movement.
- Quality of acquired data: the data is not affected by environmental factors such as temperature

and does not require post-processing, except for sonar readings, which may be influenced by environmental conditions such as ice or obstacles on water surface. The data collected by magnetic collars is sensitive to debris and biological phenomena such as biofouling.

- Data usage: the data is not integrated into BIM systems, but is managed through GIS platforms, as it concerns the external geological and hydraulic context of the structure.

Concrete corrosion sensors non-invasively monitor the parameters that promote reinforcement degradation. These are low-cost, non-invasive tools and are suitable even for areas that are difficult to access. They are used mainly to assess the condition of pre-stressed reinforcement and to monitor damages in areas where the concrete cover is damaged or missing.

- Expected output: the collected data show how the electrical signal changes over time.
- Data usage: data can be shared within monitoring systems, but it is not possible to average the reading from multiple sensors, as each measurement is related to a specific point on the structure.

Temperature and humidity sensors monitor the environmental conditions of infrastructures, both inside and outside the concrete, especially in new works. Temperature sensors can be integrated into other devices or placed near acquisition units, while humidity sensors measure the external humidity level.

- Quality of collected data: the data is not reprocessed but is used to support and correct the measurements of other sensors.
- Data usage: in monitoring systems (BMS), information is shared at the sensor, element and structure level, providing a useful framework for management and maintenance.

Static sensors

Corrosion, humidity and temperature sensors

Concrete corrosion sensors measure small electrical variations between a point in the concrete and an external point. These variations are converted into measurable indicators to detect for ex. chloride contamination or pH variations

Temperature and humidity sensors are used to monitor the environmental conditions of the infrastructures, both outside and inside the concrete

Load cells

To measure the state of stress in structural elements. Cells can be mechanical, hydraulic, electrical, or vibrating wire strain-gauge. They are installed with distribution plates to ensure a uniform contact and detect the strain caused by the load applied. They monitor stress loss in pre-compressed elements, tie rods, points of support, and control ground pressure on containment structures.

Pendulum

Used to monitor rotations and displacements in large structures. Its functioning is based on the plumb bob principle: a mass suspended from a flexible thread orients itself according to the gravitational vertical, so as to measure the displacement of structural points with respect to this direction. Installed to detect stack rotations and displacements in rocky slopes.

Vibrating wire strain gauge

Used to measure strains in structural elements, both in stress and compression. It is based on a steel rope stretched between two disks, excited by an electromagnetic coil that induces vibration. The vibration frequency, detected by an acquisition unit, is proportional to the strain experienced by the structure. Used in Gerber saddles and in scaffolding midpoints.

Timed mobile rod

composed by a vertical tube with an internal rod who moves owing to an electric engine. The engine rpm, detected by a tachometer, allows to determine the vertical displacement of the rod and thus the degree of erosion.

Displacement transducers or LVDT (Linear Variable Differential Transformer)

Used to measure the linear displacement between two nearby points. They detect the movement of a nucleus inside a metal cylinder, along a single axis. This kind of sensor is particularly suitable to monitor the partial movements between structural elements such as girders, stacks, abutments, joints and support devices.

Sonar

A more accessible technology, mounted directly on piers or substructures. It uses sound waves to measure the riverbed depth, detecting variations indicating the development of the erosion. However, the quality of data can be influenced by environmental conditions such as ice or obstacles on the surface of the water

Float-Out Devices

Inserted at different depths of the riverbeds. When the sediment is removed, the sensor resurfaces and sends a wireless signal to data loggers. This system allows the monitoring of the development of the erosion over time, with facilitated installation n dry beds and more complex installation in underwater environments, where the intervention of divers is needed

Magnetic sliding collars

Sliding along a rod as the sediment erodes, activating magnetic triggers enabling to detect the depth reached. They are easy to install but sensitive to debris and biological phenomena such as biofouling.

Dynamic sensors

Dynamic sensors are used to register the responses of structure to rapid and discontinuous events, such as the passage of vehicles. Unlike static sensors, which monitor slow variations, these devices must acquire high-frequency data (around 100-200 samples per second) to detect short duration phenomena.

Monitoring can happen in two ways: with periodic measurements, recording short traces every 12-24 hours, or through threshold events, which activate the recording when specific acceleration values are exceeded. The primary parameter measured is acceleration, useful to assess the dynamic behaviour of the structure and identify any potential anomalies.

Strain gauges are sensors used to measure the strains of a structure when it is subjected to stresses. They detect changes in electrical resistance caused by compression or traction. The sensor consists of a metal foil on a flexible support, which deforms together with the structure and transmits the signal. There are several configurations, such as biaxial and triaxial rosettes, which allow strain to be measured in multiple directions. These sensors are particularly useful to monitor dynamic stresses, for example those caused by traffic on bridges and viaducts and are often installed at the most critical point of the girders.

- Expected output: the data acquired shows strain changes over time.
- Quality of the acquired data: to be of use, It must be filtered to remove environmental interferences.
- Data usage: in monitoring systems, it is possible to share immediate measures, safety limit and data chronology, both at sensor and structural element level.

Accelerometers are sensors measuring a structure accelerations and vibrations, useful to understand dynamic behaviours and identify potential anomalies. There are several typologies: capacitive MEMS sensors, more economic and compact; piezoresistive sensors, suitable for vibrations over a wide frequency range; and piezoelectrical sensors, highly accurate and sensitive, ideal for in-depth monitoring. These sensors are installed at strategic locations such as girders, joints and impost blocks to detect vibrations caused by traffic or impulsive events.

Expected output: the acquired data shows acceleration over time and, after a cleaning phase, enables to identify natural frequences and the structure ways of vibrating, essential information to assess stability and prevent damages.

Quality of acquired data: to be of use, it must be filtered to remove environmental interferences.

Data usage: in monitoring systems, accelerometers share data including maximum accelerations, events counting and dynamic analyses (frequences and MAC coefficients), useful to assess safety and plan interventions.

Evolutions and innovations: new monitoring frontiers

Optical fibre sensors

New technologies are transforming infrastructure monitoring, offering faster and more cost-effective solutions than legacy sensors, while maintaining good data quality. In particular, in case of large and complex structures including bridges, viaducts and tunnels, monitoring requires many resources and long timing. To overcome these difficulties, innovative devices such as fibre sensors and satellite technologies are being tested, enabling to collect frequent, precise and easily accessible information. These solutions, still under development, have only been partially applied to the sector and do not yet have consolidated studies in the infrastructure sector. However, they represent a promising opportunity to improve maintenance efficiency and sustainability.

Fibre sensors represent an advanced technology for structural monitoring. They consist of glass filaments or polymers which transmit light within a core protected by external layers. When the structure deforms, the fibre undergoes changes that modify light behaviours, allowing to detect parameters such as strains, displacements, tensions and temperature.

There are different configurations:

- single sensors, for accurate measurements;
- nearly-distributed, collecting data in specific points along the fibre;
- distributed, which continuously monitor the entire length of the structure.

The main technologies are:

- Fibre Bragg Gratings (FBG), ideal to measure strains and temperature, corrosion resistance and interferences with high accuracy;
- Fabry-Pérot, short sensors detecting tensions through changes in optical cavities;
- Brillouin, for tension and temperature distributed measures;
- SOFO, using two fibres to compensate thermal effects and measure strains;
- micro-bending, based on changes in light intensity owing to curvatures;
- Raman scattering, for the continuous temperature monitoring along the fibre.

Their advantages include high accuracy, resistance to external agents and long-distance monitoring but require additional protection to prevent mechanical damage.

COMTEL Innovation

DFOS Technology

DFOS Technology: what it is and how it works

The Distributed Fibre Optic Sensing (DFOS) technology represents a revolution in infrastructure monitoring. It transforms existing optical fibre networks in smart distributed sensors capable to detect vibrations, strains and temperature variations along dozens or hundred of km, with no infrastructural changes. Each meter of fibre becomes a point di observation, with resolution up to 10 meters and sensitivity to nanometric variations and thousandths of degrees.
The operating principle is based on optical backscattering: laser pulses sent along the fibre interact with micro-glass irregularities and external turbulence (vibrations, temperature, pressure). Reflection analysis enables to recreate real-time physical events along the entire length of the cable.

DFOS systems exploit three types of scattering:

- *Rayleigh*: sensitive to vibrations (DAS – Distributed Acoustic Sensing).
- *Raman*: sensitive to temperature (DTS – Distributed Temperature Sensing).
- *Brillouin*: sensitive to strains (DSS – Distributed Strain Sensing).

Advantages of DFOS technology

Compared to traditional sensors, DFOS offers:

- Ongoing coverage up to 100 km with a single interrogator.
- Thousands of virtual points along the fibre, against few point sensors.
- Non-invasive installation: through existing fibre, without field power.
- Centralised maintenance and operational cost reduction up to 60%.
- Electromagnetic immunity and robustness in hostile environment (tunnel, submarine cables).
- High sensitivity and low latency for real-time monitoring.

These advantages enable the transition from reactive to predictive maintenance, improving safety, service continuity and sustainability.

Applications and use cases

DFOS is already used in critical sectors:

- Oil & Gas: monitoring of oil and gas pipelines to detect leaks and structural losses.
  - *Keystone Pipeline case (4.300 km, Nord America): real-time loss detection with <10 m accuracy, reducing intervention times from hours to minutes.*
- Infrastructures: bridges, dams, tunnels, railway and road networks.
  - *Øresund Bridge (Denmark-Sweden): monitoring strains and vibrations induced by traffic and wind.*
  - *Itaipu Dam (Brazil-Paraguay): early detection of losses and infiltrations.*
- Smart Road and Smart City
  - *The NEC FOSS platform integrates DFOS with AI to classify events and manage traffic. Results: 95% accuracy in automatic detection, reduction of traffic forecast errors by 80%. For example, it is possible to assess the driving risks caused by speed, incidents, traffic congestion and weather conditions, including rain and freezing of the road surface.*
- European projects:
  - *FORESIGHT (Horizon UE): seismic monitoring with optical cables inside the buildings, reduction of alert times by 90%.*
  - *ECSTATIC: monitoring of submarine cables to detect micro-seisms and tsunamis.*

Operational benefits and perspectives

- Prevention of critical malfunctions (ex. oil pipelines, water networks, bridges, telecommunication networks).
- Early warning for environmental events (seisms, landslides, floods).
- Operational safety: detection of intrusions and anomalies.
- Cost reduction: up to 60% compared to traditional systems.
- Sustainability: use of existing infrastructure and environmental impact reduction.

DFOS is a key technology for Smart Infrastructure, capable of transforming passive networks in active, smart and resilient sensorial systems. Owing to the integration with AI and IoT, it can power dynamic Digital Twins in roads, bridges and urban networks for a predictive and resilient governance of critical infrastructure improving safety, efficiency and sustainability.

Remote sensing technologies

Remote sensing technologies vary according to the technological solution adopted.

- TInRAR is a remote sensing technique enabling to concurrently measure structure and infrastructure displacements on several points, with high sampling rates. This allows both static and dynamic analyses to be carried out without installing sensors on the structure, exploiting the natural reflectivity of microwaves. The system employs an interferometric radar located on site, which calculates displacements along the line of sight by comparing phase variations of electromagnetic waves emitted and reflected over time. It is particularly suitable for vertical or horizontal structures, such as bridges and towers, and requires stable locations to get more perspectives. The accuracy varies from tenths to a few millimetres and depends on atmospheric conditions. Among the main advantages are the ability to operate under any environmental and lighting condition, rapid data acquisition and continuous monitoring without the need to apply targets to the structure.
- A-DInSAR is an advanced monitoring system using radar satellite images to detect soil strains over time with great accuracy. Owing to the analysis of historical records managed by space agencies, it is possible to reconstruct the evolution of geological and structural phenomena, including subsidence or soil movements. Compared to classic interferometric radar, A-DInSAR overcomes the atmospheric limitations using many images and stable reference points over time. The main advantage is the ability to observe vast areas with reduced costs and times, even when data is not constant, since it depends on the passage of satellites in orbit. This technology, still under development, has been applied experimentally to bridge monitoring, with remarkable potential for large-scale infrastructure monitoring.

Satellite Monitoring

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Given the specific nature of the energy, environmental and infrastructure sectors, having large-scale, regularly updated information is strategic. This data supports decision-making by supervisors and public entities in the short, medium and long term, especially in today's context, when energy efficiency and sustainable socioeconomic development are essential. For a proper management of the environmental heritage, the monitoring of land use is crucial; for example, the way land is used strongly influence the amount of carbon that soil can retain. Territorial infrastructure and urban development led to a real soil sealing with waterproof layer. In this context, satellite technology supports many surveys and analyses to mitigate these changes and improve urban planning.

Copernicus, the European Earth monitoring programme, is one of the main sources of high-resolution images for the European Union. Among the products closely linked to urban expansion, are the Copernicus Urban Atlas, composed by harmonised maps covering hundreds of EU states towns and their surroundings; the EFTA and the Copernicus Imperviousness, i.e. a product analysing spatial distribution of artificially waterproofed areas derived from a semi-automatic classification, based on the Normalised Difference Vegetation Index - NDVI.

Both services produce change maps, i.e. maps useful for understanding urban growth and its transformations by comparing different time periods.

Space technologies for Earth observation use both passive hyperspectral optical sensors, exploiting the electromagnetic energy emitted and reflected by the Earth's surface, and active sensors such as radar. The use of these sensors acquires images and data containing a large amount of information on the physical, chemical and biological properties of an object, a phenomenon or a territory.

In the energy, infrastructure and environmental sectors, information from satellite technologies is strategic to support:

- the election of sites where to build structures, by carrying out geotechnic, geophysics and altimetric assessments;
- the management of existing structures, assessing their efficiency over time, monitoring the invasion of spontaneous vegetation and keeping under control the damage and deterioration to which the assets are subjected;
- operational risk management, especially that deriving from natural events such as floods, fires and movement of earth masses.

Monitoring of the territory

By using and analysing satellite images, timely information can be obtained to support the planning and management of natural resources. For example, for a hydroelectric plant, satellite detections can accurately quantify the state of water resources and the snow accumulated during winter. By integrating these information with the weather forecasts on future rainfalls, accurate planning for the exploitation of available resources can be carried out, and timely actions can be undertaken to ensure and integrate the necessary electricity supplies.

In 2019, the Italian mission PRISMA - Precursore IperSpettrale della Missione Applicativa – saw the launch into orbit of a hyperspectral device capable to work in numerous allocated bands, from Vnir-Visible and Near InfraRed up to Swir-Short Wave InfraRed.

Unlike passive satellite optical sensors recording the solar radiation reflected by our planet in a limited number of spectral bands (about ten at most), PRISMA can acquire ip to 240. This allows to carry out a Space chemical and physical analysis of the areas under scrutiny, providing valuable information on the availability of physical resources, and supporting the prevention of natural and anthropic risks (among which the hydrogeological risk and soil pollution), cultural heritage monitoring, agricultural activities and the exploitation of mineral resources. The system also makes it possible to obtain information and data related to environmental aspects, specifically:

- water resources, measuring water turbidity at every point in the reservoir, detecting the clearest waters and algae colonies;
- the degree of water absorption by forests, which can provide an early warning signal of fire risk;
- the presence of gas fires related to oil extraction, determining their extension and recognising chemicals generated by combustion from their spectral footprint.

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By reducing the need for human inspections in critical areas, satellite image data acquisition helps to safeguard the physical safety of operators, who vice versa would be exposed to the risks of a hostile environment even for a mere acquisition of information. Likewise, significant cost reductions are possible, making network and infrastructure inspections more efficient, reducing the need of onerous inspections in terms of costs and time.

Monitoring of infrastructures and artifacts

Infrastructure monitoring over vast areas generally requires significant economic and time resources often resulting in complex implementation. The use of satellite technologies allows to overcome these limitations.

In addition to using satellite images, radars and other sensors, such as payload on board satellites, can provide highly precise measurements and data which allow an extremely accurate monitoring of the areas on which the infrastructures are distributed, enabling inspection planning, the establishment of a scale of priorities for on-site investigations and maintenance intervention planning, based on the frequent, accurate information which can be integrated with other sources.

This is the case of interferometry RADAR systems, satellite devices with Synthetic Aperture Radar technology - SAR which can obtain radar images of the area under investigation with high resolutions both in range and Azimut directions.

These systems enable to create historical series of ground movements and to understand the development of deformation phenomena affecting infrastructures; starting from the latter, through RADAR electromagnetic signal processing, it is possible to improve technical performance in terms of accuracy, making it a methodology applicable in near-real time.

In the preliminary phase of the works, territorial analysis enables to employ satellite technologies to identify the optimal route along which to place linear infrastructures, or to use thematic maps related to geomorphological features of the area in object.

During the management phase, applications are available to monitor territorial stability before, during and after construction. These applications also include monitoring and analysis of the impact of the relevant infrastructure on the surrounding environment.

Through 3D and 4D Multidimensional SAR technologies, high-resolution three-dimensional reconstructions of the scene can be produced, suitable for urban environment, while enabling carefully monitoring of temporal ground strain.

The availability of high-resolution space data provided by Cosmo-Skymed satellite sensors allows to estimate millimetric strains of single ground structures, including those due to thermal expansion phenomena (5D Imaging).

Emergency management

In addition to ordinary planning and management activities, a particularly important role is played by emergency management, especially when dealing with natural disastrous events having ever-increasing frequency and intensity, and to which our national territory appears to be particularly susceptible.

The Copernicus Emergency Management Service - EMS provides early warning information on extreme events such as floods, fires or other potentially harmful natural events.

The system is also capable of producing updated maps containing information on past events, which can be used for rescue management and for monitoring the evolution of the event.

EMS Copernicus is accessible to all bodies involved in the European Civil Protection mechanism and to other regional, national and international organisations dealing with civil protection, to the European Commission and EU Agencies.

In the emergency management context, ITHACA is responsible for acquiring, processing and organising on-site data, data from planes/drones, data from IoT sensors, and data from geospatial databases and satellite sources in a structural way, to create high value-added maps.

The service is designed to make data more accessible to users and to speed up on-site actions. Companies use the Copernicus system devoted to Rapid Mapping to create thematic maps and vector data. Ithaca supports final customers in various application domains, such as agriculture, forest management and silviculture, environmental monitoring, mobility information.

URBan ANthrpogenic heat FLUX from Earth observation Satellites – URBANFLUXES is a H2020 project financed by the EU to study urban heating, through the combined use of satellite images and conventional meteorological measurements, isolating the urban energy balance from the anthropogenic heat flux.

Project goals:

- providing data related to anthropogenic heat to several applications, including climate models, to assess the effect of anthropogenic heat on the Earth system;
- building energy models to characterise the heat exchange paths between buildings and atmosphere/soil/water;
- supporting decisions related to sustainable urban planning and the mapping of emissions related to energy consumption.

Monitoring via Global Navigation Satellite Systems signals

Innovative systems capable of generating information and 2.5D (i.e. 3D level-of-detail) maps can be realised using the Global Navigation Satellite Systems signals - GNSS (see Cap 2.5), available at global level.

The use of GNSS sensors enables a highly accurate monitoring of position variations.

This use is applied in territorial or infrastructure management, enabling, for example, to monitor soil strain, landslide movements or the displacement of various kinds of buildings, bridges and constructions.

The typology of GNSS sensors is varied. For applications requiring highly accurate monitoring, high-performance professional sensors and receives which monitor variations of a few centimetres (or of a few millimetres) can be used. In other cases, sensors with less accuracy can be used to ensure low-cost monitoring of infrastructures or territories. Moreover, through advanced GNSS signal processing techniques and their integration with other data provided by Earth observation systems, it is possible to create 3D maps of the territory. Using these techniques, Digital Twins of the monitored territory or infrastructure can be developed, enabling even more precise calibration of monitoring and maintenance activities.

Complementary technologies

Non-destructive testing (NDT)

The non-destructive testing techniques (NDT) are essential in SHM, enabling to assess the structure's state, integrity and health without causing damage. Main methods to detect faults, monitor structural health and analyse materials such as concrete, steel and composite are ground-penetrating radar, infrared thermography, optical fibres, acoustic emission, ultrasonic tests. Progresses in NDT, such as wireless connectivity, continuous monitoring and advanced sensors, improve the structural assessment accuracy and efficiency, facilitating proactive maintenance, safety and durability of critical infrastructure.

Non-destructive technologies (NDT)

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Non-destructive controls (NDT) represent a set of analysis techniques designed to inspect the proprieties of a material, component or structure without compromising its integrity and usage. This approach allows to carry out accurate and in-depth assessments without causing damage, ensuring the operational continuity and the safety of the infrastructures. The main objective is to obtain a quality control (QC) on materials and systems in an economically advantageous way, reducing risks and costs associated to invasive inspections.

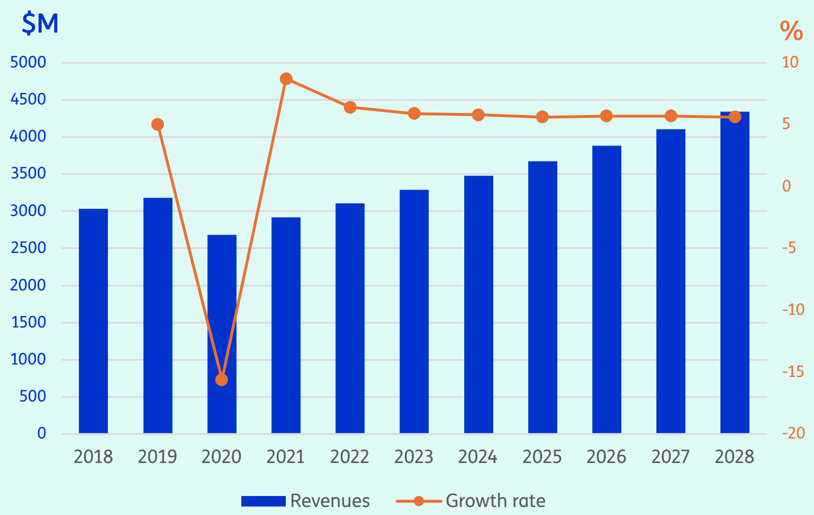
The global market of the consolidated NDT equipment has reached a value of 2.9 billion dollars, with a CAGR estimated growth of a of 5,8%, destined to exceed 4.3 billion dollars by 2028.

This expansion is led by the need to monitor aging infrastructures, especially in advancing economies, and by a growing attention to safety in the construction and industrial sectors.

Inspection and maintenance increasingly resort to non-destructive testing equipment tried to detect defects, inspect wall gauge and identify cracks.

Consolidated NDT Equipment
Revenue forecast, globale, 2018-2028

CAGR 2018-2028
5.8%



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MAIN CONSOLIDATED NDT TECHNOLOGIES

The most consolidated non-destructive testing technologies mainly include radiographic (RT) and ultrasound (UT) equipment, both used for decades to detect defects, measure gauges and assess the quality of the welds.

Radiographic Testing (RT)

Radiography uses X-rays or gamma to detect hidden defects within the materials. It is used both in labs and on field, with digital solutions which are progressively replacing conventional radiology owing to reduced exposure times and greater efficiency. The main applications include:

- Inspection of welds and fusioni.
- Measuring wall thickness.
- Corrosion mapping.
- Verification of concrete reinforcement material.

RT global market has a value of 1.4 billion dollars and grows at a CAGR of 4.6%.

However, radiography has some limitations: it requires direct access to the object and involves risks linked to radiations, as well as a requiring highly qualified staff to interpret images.

Ultrasonic Testing (UT)

Ultrasounds technology has been used for over sixty years and is based on the usage of piezoelectric ultrasonic or laser-generated waves to detect cracks, defects and gauge variations. It is available in automatised and portable versions, prevalently in energy plants. The main advantages compared to the radiography are:

- Greater safety (non emitting radiations).
- Ability to detect defects parallel to the surface.
- Flexibility owing to angled probes.
- UT global market has a value of 774 million dollars, with an estimated growth of 6% per year.

The market of portable devices has been valued at 491 million dollars and represents 63% of the global UT sector (2022), owing to their practicality and ability to acquire and analyse data directly on-site.

Lifecycle stage	Revenues	Revenues	Growth rate in the base year
Maturity	1,363.1 M$ (2021)	1,867.1 M$ (2028)	6.7% (2021)
Compound annual growth rate	**Number of competitors**	**Level of technical change**	**Concentration**
40.6% (2021-2028)	25 - 50 (active competitors in 2021)	5 (scale: 1 [low] to 10 [high])	25% (Revenue share held by the top 3 companies)

Lifecycle stage	Revenues	Revenues	Growth rate in the base year
Maturity	774.8 M$ (2021)	1,165.8 M$ (2028)	100.1% (2021)
Compound annual growth rate	**Number of competitors**	**Level of technical change**	**Concentration**
60.0% (2021-2028)	50 - 100 (active competitors in 2021)	5 (scale: 1 [low] to 10 [high])	77.7% (Revenue share held by the top 3 companies)

NEW TECHNOLOGIES EMERGING IN NDT

In addition to consolidated solutions, the sector is evolving towards more sophisticated technologies, integrated with robotics and artificial intelligence. Among the most promising we find:

Total Focalisation Method (TFM)

TFM is an advanced technique based on algorithms that reconstruct high-resolution images exploiting data acquired from transducers arrays. Integrated with robotic systems and drones, it allows inspections in areas difficult to reach, reducing times and costs. The advantages include:

- Greater accuracy in defect localisation.
- Automation of the data collection process.
- Reducing human error and increasing productivity.

A significant example is the use of robots for NDT inspections in the energy sector by Gecko Robotics. The integration of TFM with scanners and probes enabled to eliminate the need of scaffoldings and complex accesses, accelerating the activity and improving the quality of data.

Laser Shearography (LS)

Optical technique which irradiates the object with laser light and analyses the variations of the interference pattern (speckle) before and after a stress. It is ideal to detect superficial and sub-superficial defects in complex materials such as composite. The advantages:

- Rapidity of inspection (up to 1 m^2 per minute).
- Ability to identify defects invisible for other techniques.
- Applications in aerospace, automotive and turbine.

Infrared Thermography (IRT)

Based on the acquisition of thermal radiations, thermography generates images (thermograms) which detect anomalies in temperature distribution. It is used for:

- Monitoring of electrical and mechanical systems.
- Analysis of composite materials.
- Identification of hotspots and structural defects.

The IRT is a mature technology, but its integration with AI and machine learning increases its accuracy and reduces the operative complexity.

Terahertz Technology (THz NDT)

It uses electromagnetic waves in the terahertz band to measure gauges and detect defects in non-conductive materials. allows 2D and 3D imaging with high accuracy, finding application in sectors such as aerospace and electronics.

OVERALL BENEFITS OF NDT TECHNOLOGIES

NDT techniques offer strategic advantages for infrastructure monitoring:

- Non-invasive inspections: preserve structure integrity.
- Predictive maintenance: enabling to anticipate malfunctions and plan targeted interventions.
- Operative cost reduction: less plant shutdowns and greater efficiency.
- Safety and reliability: identify hidden defects before they become critical.
- Automation and digitalisation: integration with robots, drones and software for advanced analyses and real-time data sharing.

INFRASTRUCTURE MONITORING APPLICATIONS

Today NDT technologies are essential to ensure the safety of:

- Bridges and viaducts: crack, corrosion and strain detection.
- Dams and pipelines: control of gauges and structural integrity.
- Energy plants: weld and critical components assessments.
- Aerospace and automotive sectors: control of composite materials and joints.

Software and 4,0 Industry roles

Despite the success of NDT equipment and the tangible impact that consolidated and emergent solutions have had across industrial sectors, the overall growth of the market is limited by the continuous presence of complex user interfaces, inefficient workflows, complications in data interpretation, lack of traceability and obstacles in data sharing.

The future of NDT is strictly linked to digitalisation. The adoption of advanced software and AI/ML algorithms enables:

- Intuitive interfaces to simplify operations.
- Predictive analyses to reduce errors and revisions.
- Real-time data sharing among distributed teams.
- Traceability and consistency of the inspection processes.

In the past, hardware represented nearly 95% of the sector's sales, but the situation is changing, since producers realised that equipment-based revenue generation is increasingly saturated. This is why they are looking at software solutions to add value for customers and increase price/performance ration of their products.

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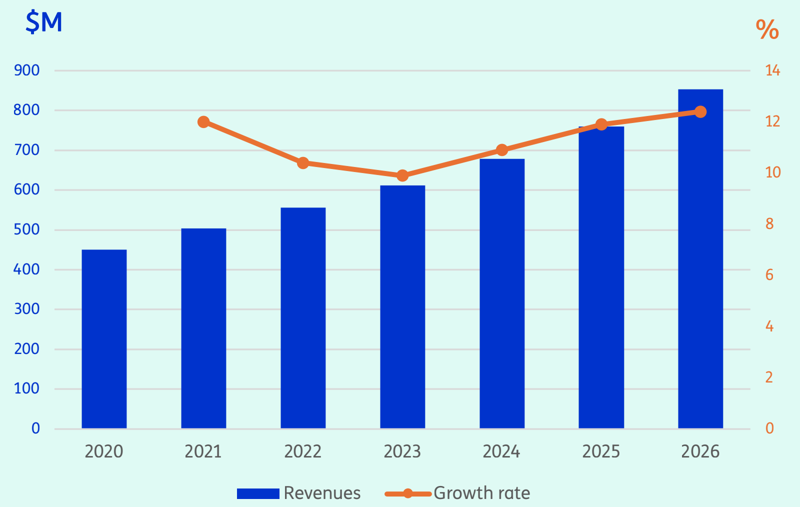
The development of new software-centric business models is therefore become essential to achieve higher growth, enable sustainability and create a competitive differentiation.

NDT Software
Revenue forecast, global, 2020-2026

CAGR 2021-2026
11.1%



Many NDT equipment manufacturing companies with relevant sales have already invested in software and developed a business model focused on it or are about to do so.
However, many smaller companies have been slower or unable to undertake these initiatives. Frost & Sullivan's analysis suggests that software can provide value to customers and expand hardware capacity. Companies of all revenue ranges should therefore focus on developing appropriate strategies.

Overall, NDT software global market has a value of 504 million dollars and is expanding at a CAGR of 11.1%, with an expected value of over 854 million dollars in 2026.

The integrated software sector is the largest. Because solutions are implicitly sold with hardware, growth will mirror that of the equipment.
With 59% of the total market, integrated software is the dominant sector, but standalone software is the fastest growing. Providers offer interfaces easy to use and multiple features and functionalities. In 2022, the global market of standalone software amounted to 208 million dollars. This figure is expected to reach around 406 million dollars by 2026, with a CAGR almost up to 18%.

Despite the entry of new equipment and the arrival of software solutions, third-party NDT services remain the cornerstone of the entire control sector.
Overall, in 2020 generated revenues equal to 8.9 billion dollars at global level, which are expected to exceed 10.4 billion dollars in 2025, with a CAGR of 3.2%.

NDT technologies are redefining the concept of infrastructure maintenance and safety.
From consolidated methods such as radiography and ultrasounds, to more innovative solutions such as TFM, laser shearography and IR thermography, the sector goes towards a predictive, automatised and digital approach. The integration with robotics, drones and software platforms speed up inspections, improves data quality and reduces costs, making these techniques essential to face the resilience and sustainability challenges of modern infrastructure.

Building Information Modelling (BIM)

BIM (Building Information Modelling) is a process that uses a smart and tri-dimensional digital model to manage information on buildings or civil works throughout their entire life cycle, from design and construction to maintenance and decommissioning. It provides a powerful platform offering visualisation, interoperability and cooperation tools, enabling the monitoring of all project phases. Integrating BIM with traditional monitoring techniques also makes it possible to organise and visualise large amounts of sensor data, facilitating damage detection and the assessment of structural condition over time.

Integration between BIM and SHM simplifies data processing and supports real-time interaction between monitoring data and digital models, fostering a new level of cooperation and efficiency in structural control. Consequently, SHM systems can help diagnose design defects, optimise sensor placement and improve equipment management, ultimately increasing monitoring accuracy and reliability.

Digital Twins

Digital twins represent an innovative approach exploiting advanced technologies to improve the monitoring and maintenance of critical infrastructure. This technology creates virtual replicas of physical assets, updated in real time through sensor data. This enables to simulate conditions, predict scenarios and take informed decisions on maintenance strategies.

By integrating measurement data with computational models, digital twins provide a comprehensive picture of structural conditions, enabling real-time and in-depth analyses of structural behaviours. They surpass manual inspections in both accuracy and promptness, making maintenance more proactive and efficient. When applied to bridges, buildings and wind turbines, digital twins, combined with IoT data, enhance understanding of structural behaviour, increase safety, reduce risks and optimise asset management, ultimately preventing costly disruptions. In short, they represent a transformative solution that improves infrastructure reliability, efficiency and duration.

Robotics and drones

Robotic and drone technologies are essential for the evolution of SMH practices, providing innovative solutions for inspecting critical infrastructure defects, assessing structural conditions and supporting monitoring activities. Drones equipped with visual sensors, including cameras and LiDARs, are widely used for aerial inspections of complex structures such as bridges, towers and wind turbines. They offer agility, access to hard-to-reach areas and improved operational safety.

Visual sensors enable automatic crack detection through machine-learning algorithms and image-processing techniques, while LiDAR sensors generate accurate 3D surface models, facilitating reconstruction and detection of anomalies that are not visible with traditional methods.

Drones and robots, potentiated by high-resolution cameras, thermo-cameras and multispectral sensors, provide an enormous amount of data that, once processed by Artificial Intelligence algorithms, can be transformed into highly valuable information for supervisory bodies.

Applying technologies such as Computer Vision enables the automatic recognition of images and objects. For example, a drone can detect an unstable boulder within the perimeter of a structure, a disconnected high-voltage cable dangerously close to a storage area containing inflammable material, or identify photovoltaic panels damaged by severe weather events. Owing to self-learning algorithms, AI can connect and compare images collected by drone cameras with predefined models and automatically trigger alerts for operators.

The integration of robotics and drones into structural monitoring improves accuracy and efficiency, enables the timely detection of challenges, supports preventive maintenance strategies and contributes to the safety and durability of the infrastructure.

CHAPTER 2: Electrical infrastructure

The role of smart grids in the new energy era

In both ecologic and digital transitions, smart grids – i.e. smart and adaptive power networks – represent an essential response to new consumption needs, the widespread growth of renewable energy and the electrification of end uses. These networks can manage and distribute energy in a dynamic and bidirectional way, owing to the integration of digital technologies, sensors, monitoring and communication systems. Smart grid development is supported by an evolving regulatory framework.

At the European level, Directive 2019/944 promotes the integration of renewables and active consumer participation. In Italy, the PNIEC and D.L. 199/2021 support energy communities and smart management systems. Authorities such as ARERA, Terna, ENEA and RSE, together with the academic sector, are carrying out pilot projects and trials to accelerate this transformation.

From legacy networks to smart grids, *in which each node can be both a producer and a consumer of energy*

Unlike legacy networks, which were designed for a unidirectional plant-to-consumer flow, smart grids are distributed systems in which each node can act as both a producer and a consumer of energy, becoming a prosumer. These smart networks monitor real-time demand, optimise distribution, reduce losses and ensure higher reliability even during critical events.

Smart grid functioning relies on various components working synergically. Among these, smart meters form the point of contact between user and network, enabling remote and automatic consumption readings and the application of dynamic tariffs.

In Italy, the replacement programme for second generation meters, promoted by e-Distribuzione under ARERA supervision, is already underway.

A key role is played by ICT infrastructures and Internet of Things (IoT), which enable data acquisition and transmission between producers, distributors, smart buildings and users.

To complete the procedure, Energy Management Systems (EMS) balance energy locally, while the use of artificial intelligence enables the prediction of load peaks and the optimisation of network response.

Energy Management Systems (EMS)

An Energy Management System (EMS) is software which monitors, optimises and records the energy consumption of a company or plant. It uses data from sensors and measurement devices to analyse consumption trends and predict annual energy use. Owing to real-time information, the EMS may intervene in the system by adjusting parameters such as frequency, load flows and controller state, helping to reduce consumption, identify waste, predict performance and optimise energy usage to contain costs.

The system enables centralised monitoring of equipment such as HVAC plants and lighting through remote servers or IoT cloud platforms, even across multiple locations. This reduces operational costs, improves productivity and automatises management, limiting the need of human intervention. EMS determine the most efficient configurations for energy production, transmission and distribution, ensuring stability, safety and reliability. To achieve this, they use advanced functions such as static-state estimation, optimal power-flow analyses and contingency assessments, together with SCADA systems[29] for the control and acquisition of real-time data.

Beyond optimising energy use, EMS help reduce emissions and improve energy balance. They provide a comprehensive view of the system, assess the impact of disruptions and enable timely interventions to prevent cascading issues and restore normal operations.

The relationship between smart grid and Energy Management Systems (EMS) is very close: they are complementary elements which together enable a smart energy management.

Smart Grids and EMS: a complementary role

Together they enable smart energy management

- A smart grid is a physical and digital infrastructure that connects producers, consumers and devices through sensors, smart meters and communication systems. Its function is to ensure a flexible, bidirectional electricity network capable of reacting in real time to variations in supply and demand.
- EMS act as operational brains: they acquire smart grid data, analyses it and use it to optimise energy flows. EMS monitor consumption, predict load peaks, reduce waste and manage production distribution efficiently. They can also control devices such as HVAC, lighting and storage systems, integrating with IoT and cloud technologies.

Among other aspects, this synergy is crucial to integrate renewable sources, support electrical mobility and enhance the development of energy communities.

Evolution of legislative and regulatory frameworks

The Italian and European regulatory frameworks converge on common objectives: digitalisation, interoperability, renewable-energy integration and cybersecurity. National regulations (ARERA, CEI, NRRP) and European directives (EU 2019/944, Regulation 2022/869) are moving towards the adoption of smart monitoring systems to ensure the efficiency, resilience and sustainability of electricity systems.

In Italy, the smart grid regulatory framework is constantly evolving and is founded on three main pillars: ARERA decisions, CEI technical measures and NRRP measures.

ARERA has supported smart grid development through pilot projects (Decision ARG/elt 39/10) and, more recently, through communication and control requirements for distributed generating plants. Starting in 2025, plants greater than 100 kW are required to instal the Controllore Centrale di Impianto (CCI), with secure communication based on the IEC 61850 protocol, to ensure system stability and interoperability[30]. This tool enables data exchange between producers, distributors and aggregators, facilitating active network management[31].

On the technical side, CEI 0-16 and CEI 0-21 regulate the connection of active and passive users to medium and low voltage grids, introducing requirements for information exchange and data security. Recent updates have reinforced the adoption of international standards such as IEC 61850 for communication between devices and control systems[32].

NRRP and the "Italia Digitale 2026" programme support the digitalisation of electricity infrastructure, with investments for smart networks, storage systems and cybersecurity. These measures aim to facilitate the integration of renewable sources and strengthen network resilience, in line with decarbonisation objectives[33].

***NRRP and the "Italia Digitale 2026" programme** support the digitalisation of electricity infrastructure*

At the European level, the regulatory framework is driven by directives and strategic plans promoting network digitalisation and their evolution towards smart models. The EU 2019/944 Directive on the internal electricity market and the EU 2022/869 Regulation on guidelines for trans-European energy infrastructure establish rules to support the integration of renewable sources and enhance network flexibility.

In 2023, the European Commission issued the Action Plan for Grids ("Grids, the Missing Link")[34], allocating investments of 584 billion Euros by 2030 to modernise and digitalise power networks, improve long-term planning and accelerate authorisations[35].

Moreover, the European Grids Package (2025) aims to simplify procedures and strengthen cross-border cooperation, promoting the use of smart technologies for network management and supply security[36].

Smart grid components and technologies

Smart monitoring is based on an ecosystem of devices and platforms acquiring and analysing data to optimise network operations. The main technologies include[37]:

- **Advanced Metering Infrastructure (AMI):** smart meters measuring real-time consumption, supporting dynamic tariffs and detecting anomalies. They enable bidirectional communication between users and utilities.
- **IoT and Distributes sensors:** sensors installed on transformers, lines and plants to monitor electrical and environmental parameters. These devices enable automation, predictive maintenance and decentralised management.
- **Evolved SCADA:** supervision systems updated with ICT technologies to manage large volumes of data, identify disruptions and coordinate automatic resets.
- **Artificial Intelligence and Machine Learning**: algorithms analysing big data to predict disruptions, optimise energy flows and improve network response. They enable autonomous and predictive decisions.
- **Energy Storage Systems (ESS)**: storage systems integrated with sensors and algorithms to manage load/unload based on demand forecasts and renewable production.

Monitoring technologies enable to detect real-time parameters such as tension, current, temperature and loads, improving resilience and reducing outages. Components like sensors, controllers, meters and smart devices are essential for real-time energy consumption monitoring, control and automation in the industrial and commercial fields.

The growing demand for advanced measurement infrastructures, smart grids and efficient energy systems in buildings has accelerated the adoption of these technologies. Network upgrading requires significant hardware investments to ensure an efficient energy management. Robustness, reliability and scalability make these components essential for the success of the EMS.

Integration with IoT and smart grids has further enhanced these solutions, owing to data acquisition from sensors and smart meters. Moreover, cloud platforms are gaining ground due to their flexibility, scalability and remote access, making them ideal for decentralised operations.

The use of artificial intelligence and machine learning introduces predictive features, such as demand forecasting and optimisation of energy purchases, reducing the need for manual intervention and increasing efficiency.

However, growing IoT and cloud interconnection requires robust cybersecurity systems to protect data and ensure operational integrity.

Focus on enabling technologies

Below, we review some of the main technologies on which smart grids and monitoring are based.

Electrical sensors

Electricity network monitoring requires devices capable to detect essential parameters to ensure stability, efficiency and safety. Electrical sensors play this role, transforming physical quantities in digital data processed by control and management systems. These sensors, connected to SCADA or EMS systems, enable continuous load monitoring, predictive maintenance and smart management. There are 5 main families of electrical sensors:

- Current sensors: measuring electrical energy flows in the lines.
- Voltage detectors: measuring the level of tension in different points of the network.
- Power and energy sensors: measuring active, reactive and apparent power as well as consumed power.
- Frequency sensors: detecting the frequency of alternating current.
- Power quality sensors: testing power quality.

CURRENT SENSORS

Measuring energy flow in the lines.

In smart grids, these devices enable to detect overloads, unbalances and malfunctions, providing real-time data to control systems. Owing to their accuracy, they can optimise load distribution and prevent service disruptions.

STRESS SENSORS

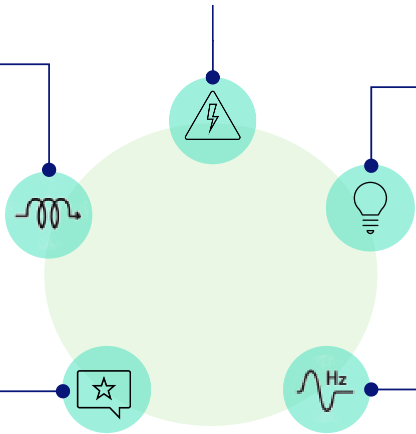
Measuring stress levels in different points of the network.

In smart grids, their role is crucial to ensure the quality of the energy and the stability of the system, especially in the presence of renewable sources which can cause stress variations. These sensors support automatic adjustment and the protection of the equipment.

POWER/ENERGY SENSORS

Measuring active, reactive and apparent power, in addition to the energy consumed.

In smart grids, these sensors are essential for balancing energy flows, dynamic invoicing and demand management. They enable utilities to optimise production and reduce losses, while consumers can monitor their own consumption in real time.



POWER QUALITY SENSORS

Controlling the quality of the energy, detecting disturbances, harmonics and stress variations.

In smart grids, these sensors ensure that the distributed energy is stable and safe, protecting sensitive equipment and improving the overall efficiency of the system

FREQUENCY SENSORS

Detecting the frequency of the alternating current, essential parameter for the stability of the system.

In smart grids, frequency monitoring enables to balance production and consumption, prevent blackout and manage the integration of the renewables, which can cause significant fluctuations.

CURRENT SENSORS	TENSION SENSORS	POWER AND ENERGY SENSORS	FREQUENCY SENSORS	POWER QUALITY SENSORS
• Current transducers (CT) • Hall effect sensors • Rogowsky coils	• Tension transducers • Tension dividers • Optical sensors	• Network analysers • Power transducers • Smart meters	• PMU (Phasor Measurement Unit) • Network analysers	• Harmonics analysers • Phase-shift sensors • Active filters

Environmental sensors

Environmental sensors are devices detecting physical and climate parameters which can affect the functioning of electrical networks and equipment. In smart grids and smart monitoring systems, these sensors have a strategic role since they prevent disruptions and optimise maintenance. The most common are:

- Temperature sensors: monitoring the heath generated by transformers, electrical panels and lines. An abnormal increase may indicate overloads or insulation problems.
- Humidity sensors: detecting the presence of humidity which can compromise electrical insulation and cause short circuits.
- Vibration sensors: used to control the state of machinery and transformers; excessive vibrations can signal wear or imminent disruptions.
- Pressure sensors: used in equipment such as switches and cooling systems.
- Air quality sensors: in close environments, they monitor dust and gas which may damage electronic components.

Internet of Things (IoT) in energy management

Internet of Things (IoT) integration is a key element in energy management systems (EMS), as it improves consumption efficiency, control and optimisation across the sectors.

All electrical and environmental sensors we have discussed are distributed IoT sensors communicating via wireless protocols (ZigBee, LoRaWAN, LTE, 5G). They can be linked to devices such as Gateway and Edge Devices, collecting sensor data and processing it locally before sending it to the cloud. Thus they reduce latency, enabling rapid decisions for critical functions such as load balancing and network protection.

Owing to IoT devices connected to EMS software, therefore, it is possible to perform real-time monitoring, data analyses and predictive maintenance. Sensors and smart meters collect information on consumption, plant performance and environmental conditions, processed by the system to optimise energy management and reduce costs.

IoT both enhances hardware and transforms services: remote monitoring, predictive maintenance and energy surveys become faster and more effective, enabling proactive and tailored interventions. In the domestic sphere, IoT enables a remote control of thermostats, lighting and household appliances, enhancing savings and comfort. In commercial buildings, IoT sensors monitor occupancy, temperature and humidity, dynamically regulating consumption. In the industrial sector, real-time machine monitoring reduces waste and plant shutdowns, improving overall efficiency.

IoT integration is useful both for local (on-premise) systems ensuring safety and immediate control, and for cloud solutions allowing the concurrent monitoring of multiple sites and providing scalability and flexibility.

Use of Artificial Intelligence in energetic infrastructure

Artificial intelligence (AI) has an increasingly central role in energy management systems (EMS), transforming their functionalities and efficiency. Owing to machine learning algorithms, EMS software can analyse large amounts of real-time data, identify consumption patterns and anomalies and predict future needs. This enables to optimise resource distribution, reduce waste and make autonomous decisions.

AI is also found in hardware: smart sensors, meters and controllers are capable of adapting to conditions without the need for human intervention, improving performance over time. AI-equipped smart meters manage energy flows with better accuracy, while controllers dynamically regulate consumption based on real conditions.

In the domestic sphere, AI enables to customise energy management: it learns users' habits and automatically regulates heating, cooling and lighting, creating more comfortable and efficient environments. In large buildings and industrial plants, AI analyses IoT sensor data, weather forecasts and occupancy times to optimise HVAC, lighting and productive processes. In the energy sector, AI is essential to predict demand, balance loads and integrate renewable sources, improving smart grid stability.

Machine Learning and energy networks

Machine learning (ML) is transforming energy management systems (EMS), providing advanced tools to optimise consumption, improve efficiency and promote innovation. Owing to data analysis and predictive capacity, ML transforms the way in which energy is managed in residential, commercial and industrial fields.

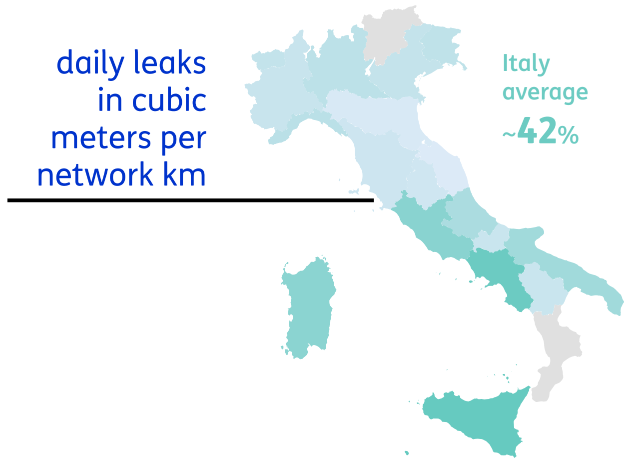
One of the most important applications is energy demand forecasting: analysing historical data and external factors such as weather, economic indicators and market trends, ML algorithms can accurately estimate future needs. This enables utilities and network operators to balance demand and supply, reduce waste and better integrate renewable sources.

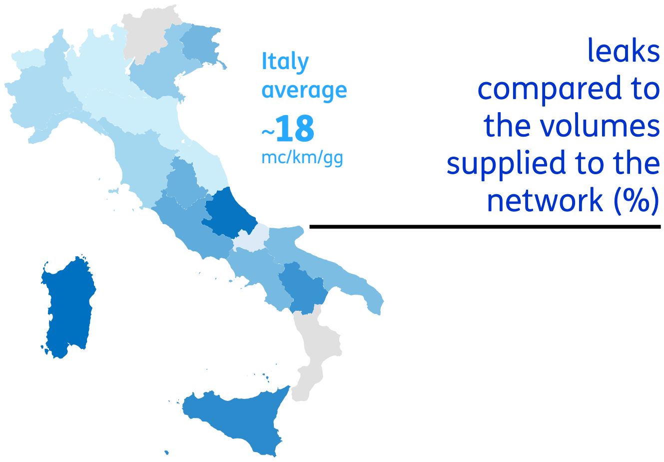
In the industrial sector, ML can anticipate equipment disruptions, programming preventive maintenance interventions and reducing plant shutdowns. In large buildings, ML optimise HVAC, lighting and safety integrated management, adapting consumption based on occupancy, weather conditions and energy prices. Moreover, ML is essential to manage storage systems and predict when to charge or discharge batteries according to demand and network conditions, maximising stored energy value.

Smart monitoring of water networks: the digitalisation revolution

Water is a vital and limited resource, essential for life, health and economic development. However, increasing pressure from population growth, climate change and pollution have made water resource management a global challenge. Under the UN World Report on the development of water resources, water scarcity is set to increase, with an estimated global shortage of 40% by 2030 if effective management and monitoring measures[38] are not adopted. According to OCSE, water demand will grow by 55% in 2050[39], making it essential to prevent waste and losses through advanced detection and monitoring techniques.

Water network monitoring is essential to ensure an efficient distribution and reduce losses. In Italy, the situation is particularly critical: around 42% of the water in the distribution network is dispersed, with peaks exceeding 50% in the South[40].





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Source: ARERA

These losses derive from pipe breakage, defective joints and illegal connections, with serious economic, social and environmental repercussions. Digitalisation and the use of smart technologies like IoT sensors and telecontrol systems are essential to face this challenge, enabling the timely detection of anomalies and predictive maintenance[41].

The main challenges affecting the national water resource management system are[42]:

1. missing and/or inefficient infrastructure;
2. drought (which in recent years happened with growing relevance and recurrence);
3. lack of investments;
4. management fragmentation;
5. water withdrawals for civil use (among the highest in Europe).

Leakage (dispersed water in the distribution network), which is one of the most immediate indicators of network efficiency, in Italy is particularly critical: according to data on the integrated water service (SII) functioning in the year 2023[43]:

- at the national level, "Linear water losses" M1a indicator marks a value of 17.9 m3/km/gg, with peaks higher than 30 m3/km/gg in the Centre-South regions;
- the "Percentage water losses" M1b indicator records a value of 41.8% across the national territory, and peaks higher than 55% in some regions of the South[44].

At global level, over two billion people live in areas subject to water stresses, and 45% of the global population has no access to safe hygienic-healthcare structures. In this context, the water network smart monitoring is not just a technical issue, but a strategic priority for water safety and the achievement of Sustainable Development Goals (SDG)[45].

To reduce waste and losses, utilities are implementing Smart Water Management (SWM) solutions based on digital technologies including cloud, IoT, 5G, smart metering and Advanced Metering Infrastructure (AMI). These tools enable:

- Near real-time consumption measurements.
- Water quality monitoring.
- Reduction of unaccounted losses (NRW) due to reading errors, unauthorised consumption or network disruptions.

IoT and cellular communications (ex. 5G) improve the infrastructure operational efficiency and resilience, enabling remote control of plants and sensors. 5G, in particular, enables an accurate real-time monitoring of the quality of industrial wastewater. Moreover, cloud solutions are gaining ground for their scalability and reduced costs, facilitating their adoption also in contexts with limited budgets.

European regulations and strategies

In Italy, the adoption of smart water monitoring systems is strongly supported by the National Recovery and Resilience Plan (NRRP), which provides for smart meter implementation, telecontrol systems and digital platforms to transform legacy networks into smart networks, improving service resilience and efficiency[46].

Other key legal references are ARERA decisions and the Regulation on the Technical Quality of the Integrated Water Service (RQTI), which establishes performance indicators and utilities incentive schemes, facilitating investments in digital solutions and continuous monitoring[47]. Moreover, UNI and ISO standards provide technical guidelines to ensure interoperability, data security and compliance with international best practices.

At the European level, the regulatory framework is driven by the Water Framework Directive (2000/60/EC), which requires Member States to adopt measures for the sustainable management of water resources, and by the Drinking Water Directive (EU 2020/2184), transposed in Italy with D.L. 23 February 2023, no. 18. The latter introduces a risk-management approach along the entire supply chain, from collection up to the point of use, and requires continuous monitoring systems to ensure water quality[48].

The European Strategy for Water Resilience (2023) promotes network digitalisation as a lever to reduce losses and improve water efficiency by 10% by 2030. Planned actions include the adoption of smart solutions, green infrastructure and smart management practices for water resources[49]. Moreover, programmes such as ICT4Water and Horizon Europe finance innovative IoT-based projects, cloud computing, digital twins and predictive analysis to optimise water network management[50].

Water monitoring technologies

Smart Meters

There are two main typologies, AMR (Automatic Meter Reading) and AMI (Advanced Metering Infrastructure).

AMR meters are smart metering technologies designed to help water companies solve problems such as access to meter data, inaccurate billing and low quality of customer service. AMR's aim is to enable utilities reduce water consumption through remote management.

Traditionally, meter readings are performed manually, whereas AMR technologies enable remote data collection, reducing operational costs and increasing accuracy. AMR solutions can be walk-by, drive-by or fixed-base, avoiding the need for on-site meter visits.

Main limit: data transmission is unidirectional. The utilities collect remote data through mobile networks or fixed lines, and cannot send commands to meters. Some Advanced AMR (AMR+) include additional modules for querying or reprogramming meters, but are less evolved compared to AMIs.

AMI is a network-based technology using a bidirectional communication between meters and central systems. In addition to AMR advantages, AMI allows:

- more frequent and detailed data collection;
- advanced analysis for billing, consumption monitoring and demand management;
- remote control functions, such as service activation/deactivation from a single location;
- integration with management data (MDM) and planning (MCI) systems;
- customer service improvement due to digital tools and automation.

AMI is considered a more advanced and smart system, with the ability to analise, store and use large volumes of data. In the following years, it will replace traditional systems in the residential, commercial and industrial sectors to meet growing demand for advanced functionalities.

Internet of Things (IoT) in water management

In **Smart Water Management**, IoT is essential to optimise and control water resource usage at domestic, community and national levels. One of the main advantages is process transparency along the whole water distribution chain, improving monitoring, loss detection and resource planning. Integrated with **Machine Learning** algorithms, IoT provides useful data and insight for analyses and reporting.

The sensors which collect information in this field, integrated with IoT technologies, transmit real-time data to platforms, enabling advanced analyses and process automation:

Flow sensors are essential devices in smart water metering systems, as they measure the quantity of water flowing through a pipe in a given time interval. Owing to this function, they enable accurate and real-time consumption monitoring, reducing waste and improving water resource management[51].

There are several technologies to measure flow:

- **Ultrasound sensors**, using sound waves to calculate flow speed and scope. They are non-invasive and very accurate, making them ideal for smart applications.
- Electromagnetic sensors, based on the electromagnetic induction principle, suitable for conductive liquids and very reliable for complex water networks.
- **Mechanic sensors**, exploiting impellers or turbines to detect flow. They are more traditional, but still used in domestic contexts.

These sensors enable:

- **Consumption monitoring** for billing and analyses.
- **Loss detection**, owing to the exposure of anomalous flow variations.
- **Distribution optimisation**, balancing pressure and network flow.
- **Sustainability support**, reducing waste and improving water resource management[52].

Integrated with IoT technologies, flow sensors transmit data to cloud platforms, where it is analysed to activate alarms, manage dynamic tariffs and plan predictive maintenance interventions.

Pressure sensors. These devices measure the force exerted by water on a surface, converting this physical quantity into a digital signal suitable for monitoring and managing water networks. The functioning principle is based on the relation between pressure and fluid height: the higher the level of water, the higher the pressure detected. This enables to measure essential parameters such as pressure in pipes, water level in reservoirs and flow, ensuring an accurate control of water infrastructure[53] (SenTec, 2022). For example, pipe pressure monitoring can detect anomalies, disruptions or losses, supporting predictive maintenance, preventing breakages and reducing operational costs.

Level sensors. These devices are designed to measure liquid height or volume in reservoirs, tanks or pipes, converting this information into a digital signal. They are essential in smart water metering systems and in the smart management of water networks[54], enabling real-time water availability monitoring and optimising distribution and storage processes[55].

Most common technologies

- **Ultrasound sensors**: measuring the distance between sensors and liquid surface through sound waves.
- **Capacitive sensors:** detecting variations of electrical capacity due to liquid presence.
- Hydrostatic pressure sensors: calculating levels from the pressure exerted by the liquid.
- **Radar sensors**: using electromagnetic waves for accurate measurements also in difficult conditions.

Water quality sensors. They monitor chemical and physical parameters which determine water potability and safety, detecting pH, turbidity, electrical conductivity, temperature, residual chlorine and, in some cases, the presence of contaminants. They are essential in smart water management systems, enabling quality standards and a prompt intervention in case of anomalies[56]. They are used in waterworks, treatment plants, distribution networks and industrial applications.

Most common technologies

- **Electrochemical sensors:** measuring pH, chlorine and conductivity.
- **Optical sensors:** measuring turbidity and colour.
- **Thermal sensors:** measuring temperature.
- **IoT advanced sensors:** integrated with cloud platforms for predictive analyses and automation.

Temperature sensors. Designed to detect and monitor the temperature of water and the surrounding environment, converting this information into digital data. They are essential in smart water metering systems and the smart management of water networks, since temperature affects water quality, bacteria formation and treatment process efficiency[57]. They are used in waterworks, treatment plants, distribution networks and domestic applications.

Most common technologies

- **Thermistor sensors:** detecting variations of electrical resistance according to temperature.
- **Infrared sensors:** measuring the temperature without direct contact.
- **Integrated IoT sensors:** transmiting real-time data to cloud platforms for predictive analyses and automation.

Sensor typology	Main function	Applications
Pressure sensors	Measuring water pressure in pipes and reservoirs	Loss detection, pump control, network security
Level sensors	Monitoring water level in reservoirs and tanks	Managing water reserves, filling automation
Flow sensors	Measuring water volumes flowing in a pipe	Billing, consumption monitoring, loss detection
Water quality sensors	Analising chemical and physical parameters (pH, turbidity, chlorine)	Potability control, water treatments, alarms
Temperature sensors	Detecting water and environment temperature	Prevention of bacteria proliferation, industrial processes

Big Data Analytics

Big Data analysis is essential to value the great amount of data collected daily by IoT devices. This technology enables to transform raw data into information supporting more accurate decisions, reducing operational costs and improving resource management. In the water sector, big data analytics enable to analyse data from different sources, i.e. maintenance records, visual and acustic sensors, rugged tablets and GPS systems. Through these analyses, it is possible to optimise network management, detect losses and improve service reliability. Moreover, predictive analysis and data mining techniques help preventing problems and planning targeted interventions, making the network more sustainable and resilient.

5G Networks

5G is the fifth generation of cellular networks, introducing advanced capabilities which transform connectivity. One of the main 5G innovations is the acceleration of the Internet of Things (IoT), which enables to connect a much larger number of devices reliably and securely, without outages. This is essential for data-driven sectors such as smart water and infrastructure management, where rapid and stable communication is essential. 5G joins the communication technologies traditionally used for water metering, based on IoT protocols, and low energy consumption networks designed to transmit data in a reliable and secure manner. These are:

NB-IoT (Narrowband Internet of Things): 3GPP standard on cellular band, ideal for long-range, low-power transmissions. Advantages: extended coverage, high indoor penetration, high security.

LoRaWAN: proprietary LPWAN protocol on non-licensed frequences, optimised for long-range, low-power communications. Advantages: reduced costs, high autonomy, ideal for remote areas.

Sigfox: global LPWAN network with proprietary protocol, designed to transmit small data packages. Advantages: minimum energy consumption, easy implementation.

Wireless M-Bus (wM-Bus): open standard for remote meter reading operating on non-licensed bands. Advantages: compatibility with existing systems, private network potential.

GSM/GPRS: traditional standard cellular technologies for data transmission. Advantages: reliability, global coverage, integration with existing infrastructures.

Edge Computing and Digital Twins

Edge computing is a key technology for smart water management. It consists in processing and analysing data directly close to its source, without sending it to remote servers. This approach enables to:

- Analyse real-time data, with immediate detection of losses, water quality issues or pump regulation.
- Reduce latency, avoiding delays that could compromise sensitive applications.
- Increase security and privacy, maintaining data within the local network and reducing the risk of transmission violations.

Owing to these features, edge computing enables water management systems to react promptly to operational condition variations, improving efficiency and reliability.

Digital twins are virtual models replicating physical systems, enabling real-time monitoring and analyses. This technology can simulate scenarios to predict system behaviours and support more informed decisions on water resources management. Owing to digital twins, it is possible to:

- constantly monitor water network conditions, detecting problems early on and applying targeted solutions.
- Predict water quality challenges through predictive analyses, adopting preventive measures before they become emergencies.

Artificial Intelligence (AI)

In managing water resources, AI can combine growth projections with infrastructure condition analyses to optimise investments. Moreover, it enables automatised inspections of water supply and sewerage networks, meter accuracy assessments and the provision of tailored online platforms for consumption monitoring, bill payment and access to updated information on water resources.

Part Two

European scenario

CHAPTER 4: Infrastructural development in the EU

From "physical connectivity" to «enabling platforms»

In the European vision, infrastructures and networks have consistently played a central role in promoting the Union's social and economic development. However, over the past thirty years, their strategic function has evolved significantly, reflecting the shifting political priorities of each historical phase.

The '90s – the establishment of the Single Market

Since the mid '80s, before the establishment of the EU through the Maastricht Treaty in 1992, the differing levels of development among the regions that made up the European Economic Community began to emerge as a significant issue. To attain a united Europe, it was necessary to overcome disparities, strengthen cohesion among EU Countries and integrate the different national economies into a large single market. To achieve "a single, integrated internal market without restrictions on the movement of goods; the removal of barriers to the free movement of people, services, and capital", a suitable infrastructure to reinforce the "physic" connections among national markets was needed. It is both an economic and a political issue: in most cases, the main infrastructure sectors – transports, energy, telecommunications, water – are almost universally public monopolies, with a few exceptions, as in the UK. This is why it was necessary to harmonise frameworks and advance towards more uniform models[58]. This process paved the way for the liberalisation of utilities and the privatisation of operators – which at the time worked in a monopoly regime – implemented in different ways across the individual Member States. Moreover, it was necessary to design a shared infrastructure development strategy. The Maastricht Treaty included a specific point (Title XII) on the implementation of shared networks: "the Community shall contribute to the establishment and development of trans-European networks in the areas of transport, telecommunications and energy infrastructures", and ensure interconnection and interoperability among national networks[59]. To this end the Cohesion Fund (1994) has been established, i.e. a specific financial tool to enable the implementation of environmental works, such as trans-European networks.

With the Trans-European Transport Network (TEN-T) project, a joint planning for road and rail infrastructure was initiated, identifying the main connection pillars. TEN-Ts address two fundamental needs:

- Territorial cohesion: reducing the gap between central and peripheral regions, promoting accessibility and economic inclusion.
- Global competitiveness: equipping Europe with modern infrastructure to compete with United States and Japan, in an era of increasing globalisation.

Similar initiatives for the integration of national energy (TEN-E) and telecommunications (eTEN) infrastructure were subsequently added to this project, as provided by the Treaty.

Early 2000s – Enlargement and digitalisation

The new millennium brought two major transformations: the enlargement of the EU to include Eastern European countries and the digital revolution. The accession of 10 new Member States with less developed and heterogeneous networks required a harmonisation strategy. The Lisbon Strategy (2000) identified a new challenge: transforming the European Union into a knowledge-based economy capable of competing in a global market. In this context, networks are not merely physical connections: they take on an immaterial dimension, becoming key innovation-enabling infrastructure supporting competitiveness and economic growth.

Following this input, in the first decade of the 2000s, investments were made for the development of broadband and digital services. 3G was launched, enabling Internet connectivity on the move. The foundations were being laid for the development of a single digital market, which became the goal of the Digital Agenda for Europe (2010), a programme due to enable the European Union to compete with the USA and Asian countries in the development of digital technologies. At the same time, the scope of TEN-T transport networks increased, including new Eastern territories to ensure territorial continuity and promote the economic development by strengthening the competitiveness of the Single Market. Following the telecommunications sector, liberalisation processes in the energy sector were gradually coming to completion and spaces were opening up for private investments and public-private partnerships.

Environmental sustainability began to assert itself on the European political agendas in the early 2000s, finding its first regulatory expression in the Water Framework Directive (2000/60/CE), which marked a turning point in the management of water resources: water was recognised as a heritage to be protected and the obligation for Member States to draw River Basin Management Plans was introduced. A few years later, the water sector has been excluded from the 2006 Service Directive (or Bolkestein Directive), preventing the liberalisation of the market planned by some EU countries. This choice reinforced the idea that water is a common good and helped to consolidate a more prudent approach in the management of water services.

The 2020s – Crisis, transition and strategic autonomy

The third decade was marked by systemic shocks: pandemic, conflicts, energy crises and geopolitical tensions. These events accelerated the review of infrastructure policies, directing them towards resilience, sustainability and strategic autonomy.

Intelligent, decarbonised, digital networks were the priorities redefined by the European Green Deal (2019), Next Generation EU (2020) and Digital Compass (2021). Europe aims to become a reference point for the ecological transition and the digital transformation of societies, but tensions and conflicts have highlighted the excessive dependency of European strategic supply chains on non-UE providers. For this reason it was necessary to promote a more autonomous and sovereign system. In this scenario, infrastructure became an enabling platform for the technological and energy sovereignty, with the aim to achieve security and independence from global supply chains.

To support this transformation, a series of financial tools were activated, specifically:

- the Recovery & Resilience Facility (2021), a temporary support device provided by the NextGenerationEU programme to revive European economies after the Covid-19 pandemic. Among its main objectives there is the generation of investments in modern and sustainable infrastructure, under the green and digital transition;

- the Digital Europe Programme (2021) for the development of "Made in Europe" cloud, AI and cybersecurity infrastructure to reduce technological dependency on other competing systems;
- RePowerEU (2022), established in response to the energy crisis following the outbreak of the Russian-Ukrainian conflict and focused on developing renewable sources and improving interconnections among the European energy systems.

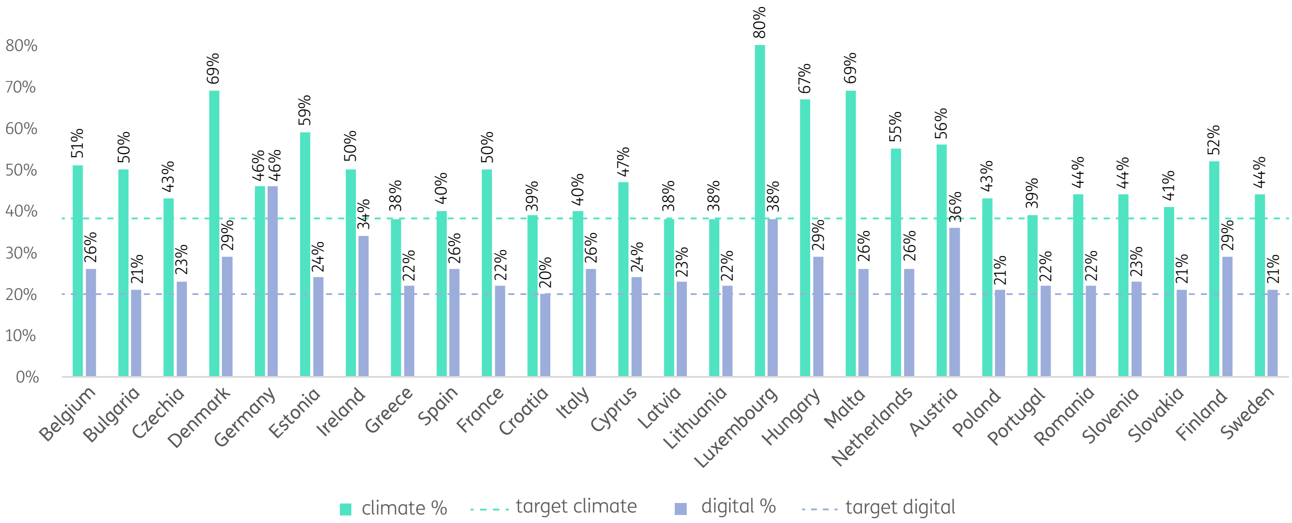
These new devices complement consolidated programmes such as the CEF (Connecting Europe Facility), launched in 2014 to promote the development of trans-European networks in the transport, energy and digital sectors. Moreover, to support projects with a greater margin of risk, the Juncker Programme – named InvestEU – was redesigned, by allocating part of the Union Budget as guarantee for the initiatives undertaken by the European Investment Bank. Finally, the IPCEIs (Important Project of Common European Interest) were strengthened, to enhance cooperation among Member States, businesses and research hubs and support innovation and technological development in strategic sectors, overcoming potential limitations and market failures and generating widespread benefits for the Union. A complex system of strategic programmes, funds, initiatives aiming to drive Europe to increase its own infrastructure provision and reinforce its technological ambitions by increasing the Union's resilience, competitiveness and economic cohesion.

Similarly to the Green Deal, the Blue Deal – proposed in 2023 by the European Economic and Social Committee (EESC) – recognised water as a strategic priority and invited the EU to adopt an integrated and resilient water policy. The proposal includes the establishment of a Blue Transition Fund to finance sustainable water infrastructure and promote water resilience in Europe. In 2025, the European Parliament resolution on water resilience strategy provides for a 10% water efficiency target by 2030. Although non-binding, this objective makes the sector enhance infrastructure efficiency.

Initiatives introduced by Next Generation EU

To contain the spread of the Covid-19 pandemic, nearly all national governments implemented population confinement measures resulting in a prolonged disruption of economic activities. To counter the effect of the crisis and relaunch the economy, the von der Leyen Commission, with the European Council support, launched an ambitious Investments Programme under Next Generation EU, to go from challenges to opportunities and build the Europe of tomorrow[60]. According to the analyses of the European Court of Auditors (ECA), the overall allocation provided by Next Generation EU exceeded 800 billion Euros at current prices. Of these, around 723.8 billion Euros were mobilised by the Recovery and Resilience Facility (338 billion Euros in grants and 385 billion Euros in loans). Since some Member States have chosen not to make use of the loans, the total amount committed by the RRF was approximately 650 billion Euros[61]. This huge volume of investments was to be directed at the post-pandemic short-term economic recovery and to drive the structural transformation of the European economy in the medium-long term (resilience), through both the green and digital transformation. To this aim, each Country had to submit National Investment Plans identifying projects to be financed by allocating at least 20% of the funds to digital transformation initiatives and 37% to the green transition. As stated in the latest implementation report, these two constraints have been met by all Member States.

Share of RRFs estimated total allocation supporting climate and digital objectives, following revision of RRFs



Source: Recovery and Resilience Facility Annual Report 2025

RRF funds allocations among energy, transport and water

The Recovery and Resilience Fund represents an innovative tool, for its financial scope, the cross-sectoral initiatives and projects it includes, and for the timeframe in which it was designed in response to the emergency. Therefore, its implementation is to be closely monitored. The latest RRF implementation report by the European Commission (October 2025) provides the most up-to-date overview of the programme's progress[62]. This shows that the completion rate of the goals and objectives to be achieved by the first quarter of 2026 is around 60%, with differences among the observation axes. More specifically, the projects included in the green transition have a 48% completion rate, those for the digital transformation around 50%. According to ECA, however, their implementation is behind schedule and the completion of several measures and interventions remains at risk. ECA's position, which speaks of a missed opportunity as to the digital transformation projects initiated by the

Union[63], also finds challenges in other areas, such as the investments planned to innovate the electricity grid and deemed insufficient to meet the growing energy demand[64], the control system implemented by the European Commission[65] and more generally the way funds have been used. The RRF "has so far contributed to a limited extent to achieving the EU's higher lever objectives or to addressing the structural challenges identified in the country-specific recommendations", valuable reflections in view of the discussion to define the new multiannual financial framework of the Union for the seven-year period 2028-2035.

The in-depth reports of the European Parliament Think Tank represent a valuable point of reference on how funds are employed to transform energy, water and transport infrastructures.

Transport

With a provision of about 83 billion Euros, equal to 12.8% of the total RRF amount, investments due to achieve a smart and sustainable transport system are at the hearth of European decarbonisation and territorial integration policies. Italy is the country which received the largest contribution in value (around 34 billion Euros, equal to 41% of the total funds allocated for a smart and sustainable mobility). Italy, Spain (9.9 billion Euros) and Germany (7.6 billion Euros) absorb 60% of the total funds allocated to this area[66].

The railway, responsible for approximately a quarter of CO_2 total emissions in the EU, absorbs around 59% of the funds, particularly for the realisation of ERTMS (European Rail Traffic Management System), which defines a common standard for train control and signalling throughout the EU. Its adoption makes the implementation of the trans-European network TEN-T more real and allows for the adoption of a more efficient traffic management system. The Commission estimates that the ERTMS completion will require a total investment of approx. 29 billion Euros, plus 26 billion from the CEF (Connecting Europe Facility) for the period 2021-27.

In addition to railway investments, the RRF's fundings also focus on sustainable urban mobility (local public transport, fleet electrification, cycling infrastructures), intermodality and integrated logistics, with a specific focus on port nodes and connections between transport modes.

Energy

The energy sector is the main beneficiary of the RRF, with more than 250 billion Euros allocated to the essential component of the green transition, equal to over 40% of the total. These funds were subsequently enhanced by the REPower EU programme (which mobilises approx. 210 billion Euros up to 2027). Countries like Italy, Spain, Germany and France are among the largest recipients of energy funds, reflecting both their economic scale and the urgency to accelerate the transition towards low emission energy systems. Italy is the largest recipient in absolute terms.

Investments are focused on renewable sources (solar photovoltaic, onshore and offshore wind, green hydrogen), for about 30-35% of the total. Then there are energy efficiency measures (rehabilitation of public and private buildings, heating/cooling networks), cross-border electrical interconnections and industrial decarbonisation.

By 2026, the National Recovery and Resilience Plans aim to:

- add 60 GW of renewable capacity, including more than 15 GW of offshore wind;
- promote an annual saving or 28 million MWh of primary energy through energy efficiency measures;

- modernise 14,000 km of transmission and distribution lines to enable the integration of renewable energy;
- deploy more than 2.5 GW of green hydrogen electrolyser capacity.

Water sector

Water sector receives approx. 12.92 billion Euros from 15 Member States' National Recovery and Resilience Plans, and extra 13 billion Euros from Cohesion Funds. Although the sector is strategic for climate resilience, it remains marginal in relative terms, accounting for less than 2% of the total RRF allocation, despite the growing investment gap in the sustainable management of EU's water resources (estimated at around 25.6 billion Euros per year).

In absolute value, Spain and Italy grant the RRF largest allocations to sustainable water management (approx. 12 billion in total, i.e. 79.5% of the total funds allocated)[67].

Investments are focused on:

- water resources management and conservation (72.3% of funds): rehabilitation of dams, optimisation of current resources use, creation or expansion of strategic reserves;
- drinking water supply compliant with efficiency criteria (19.6%): reduction of network losses, modernisation of distribution systems;
- wastewater treatment and collection (8.1%): purification compliant with energy efficiency criteria.

Investments in water network digitalisation, smart metering, remote control and predictive modelling remain limited, despite their potential to reduce network losses. Institutional fragmentation within the water sector (were competences are distributed across national, regional, local and public/private bodies) makes the coordination, planning and implementation of consistent policies more challenging.

Digital sector

The Next Generation EU programme, through the RRF (Recovery and Resilience Facility), has allocated a significant share of the European resources to the digitalisation process, with 26% of the funds for digital objectives: figure that stands at around 160 billion Euros across all UE Member States. Italy remains the main beneficiary of those resources, followed by Spain and France.

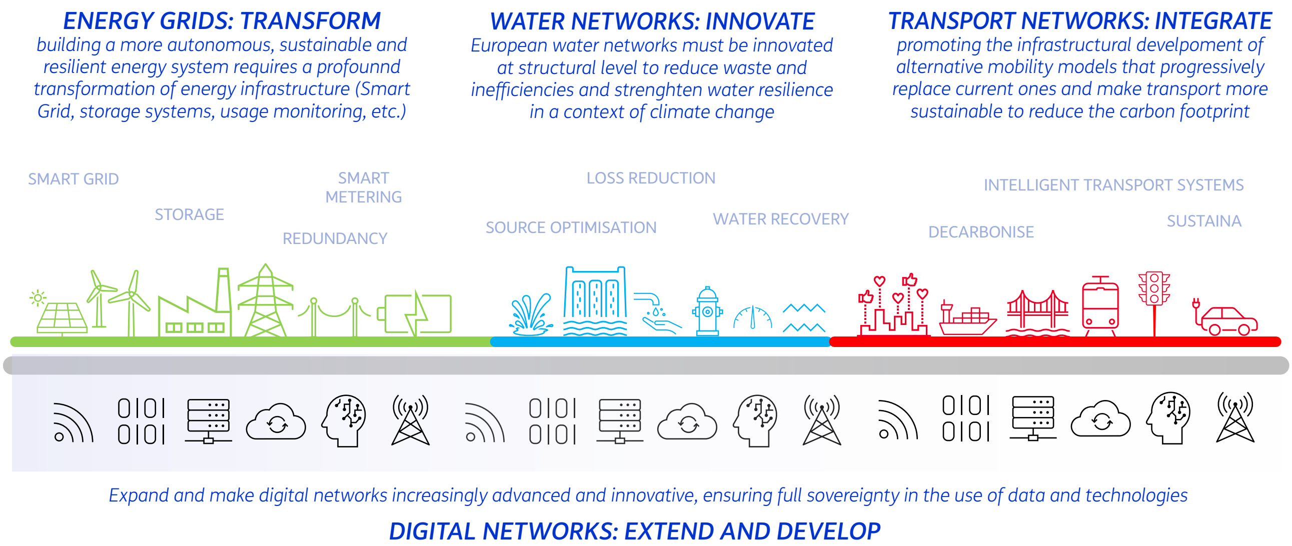
Digital public services represent the main area of investment, absorbing 37% of the allocated resources, approx. 53 billion Euros. The stated objective is to ensure full accessibility to key public services online, in accordance with the European directives on PAs digitalisation and on improving availability for citizens and businesses.

Other measures provided by the plan include strengthening digital infrastructures, promoting digital skills across the population, digitalising businesses and developing advanced cybersecurity systems.

The European Court of Auditors (ECA) found that, in December 2024, nearly half of the projects under review were behind schedule, a critical aspect given the importance of digital technologies in driving change in other strategic infrastructures:

- in the energy sector, digitalisation transforms infrastructure design, enabling smart grids, distributed storage systems, demand response systems and production/consumption real-time monitoring, facilitating the integration of renewable sources and improving the overall efficiency of the system;

- in the water sector, digital technologies bring profound innovation. IoT sensors, telemetering, AI-based predictive models and integrated management platforms enable loss detection, optimised distribution, forecasting of extreme events and improved governance;
- in the transport sector, digital platforms allow for a greater integration of different modal systems, enabling more efficient exchanges and promoting alternative mobility models. This makes a more sustainable sector impact, reducing emissions.



Network resilience, an area of growing interest

European Union resilience: towards a new paradigm

Resilience is a cross-sectoral concept applied in several contexts, from psychology to mechanics, from sociology to security. All definitions highlight the ability of the subject, be it an individual, a material or a system, to face and overcome a traumatic event, a difficult period, a crisis.

But when events occur with continuity – when we are no longer facing a single emergency but dealing with widespread and growing complexities such as economic and financial instability, climate change and shocks caused by a shifting geopolitical landscape – resilience becomes a structural requirement entailing the ability to anticipate, absorb, adapt and transform in response to a changing context. This transformative capacity should also be considered in designing infrastructures which are increasingly central and critical to our societies. The aim is to deploy networks and installation that are both functional, innovative and efficient, and capable of withstanding and adapting to potential changes in context. This feature – which until recently might have seemed unsuitable for structural works typically requiring solidity, robustness and stability – is now made possible through the use of digital technologies, subtly transforming the nature of modern infrastructures.

According to this principle, the European Commission published the “Resilience 2.0: Empowering the EU to Thrive Amid Turbulence and Uncertainty” report, outlining the fundamental transition in the EU’s concept of resilience. Recent global events lead the EU to move from a reactive to a proactive and transformative approach, defined as “Resilience 2.0”. This new model aims to withstand calamities and to predict, adapt to and transform them in response to complex and persistent challenges such as geopolitical crises and conflicts, security threats, climate and biodiversity risks, technological and demographic change and attacks on democratic values.

The war in Ukraine, along with hybrid threats active between war and peace, radically changed security perception, highlighting the need for the Union’s strategic autonomy.

Conversely, climate change fells within the systemic risks affecting infrastructures, financial markets and public health. The consequences of this phenomenon are reaching critical levels: global temperatures have exceeded the threshold of +1.5°C compared to the pre-industrial era and between 1980 and 2023 extreme events such as fires, drought and biodiversity loss in the EU generated economic losses equal to 738 billion Euros.

Preparedness and security: strategic pillars

EU preparedness is based on the ability to predict and prevent threats, also through infrastructure and smart systems. Key elements are strategic foresight, situational awareness and rapid alert.

Technology is a key enabler of these strategic pillars: sensors installed along road and railway networks or carried by vehicles and their drivers, digital twins for bridges and dams, control rooms for managing electricity and water networks, data processing models for predictive analyses. The EU' competitiveness and resilience rely on technology, as well as on risk management. Emerging technologies (quantum computing, biotechnologies, neurotechnology, robotics) offer significant potential, but require safeguards to protect rights, privacy, the environment and democracy.

The European innovation model is founded on ethical values and controlled access to data but faces obstacles as the difficulty of accessing venture capital, which is essential for technological development. To compete with the USA (market-oriented) or Chinese (state-owned) models, the EU must strengthen its approach based on values and sustainability.

Among the priority areas of intervention identified by the report, the most interesting as to the management of critical infrastructures are:

the enlargement of internal and external security through a technological and forward-looking approach exploiting civilian-military synergies. It is essential to develop secure European strategic (digital, energy, spatial) infrastructure and rationalise joint acquisitions to achieve economies of scale. Preparedness must be strengthened at all levels, from citizens to businesses, by integrating security into all policies, with a coordinated territorial perspective;

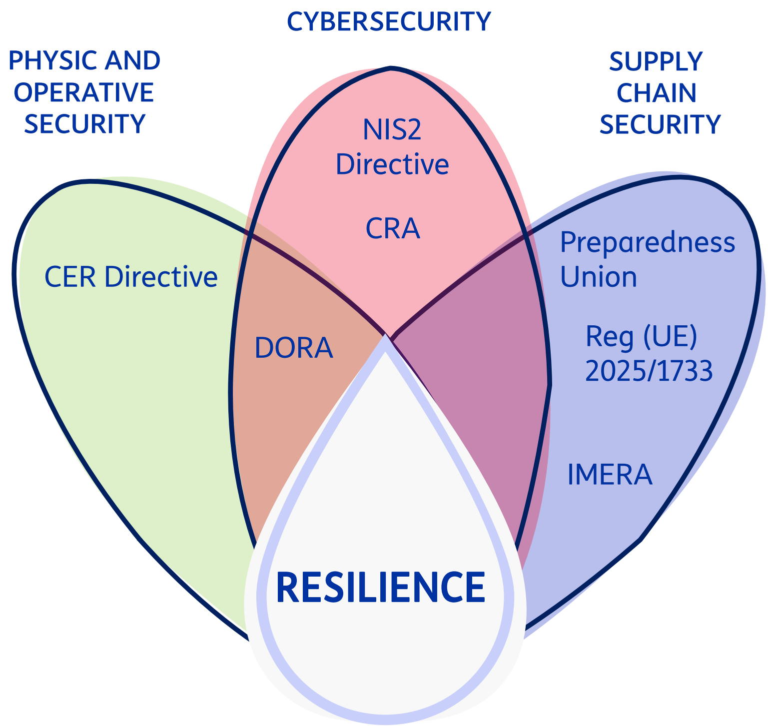
the enhancement of technology and research to enable the EU to achieve global leadership in the governance of high-impact technologies, specifically AI, by promoting secure development aligned with European values. It is essential to build research and critical infrastructure strategic autonomy, simplifying regulation for strategic projects and setting ethical and security standards. The aim is to make the EU a global reference point for responsible technological innovation, while strengthening technological sovereignty and international cooperation.

In this context, in the last few years the European Union has developed a set of directives and regulations to protect strategic infrastructures and strengthen resilience, addressing various aspects in the following areas:

physical and operational security (CER, DORA),

cybersecurity (NIS2, CRA – Cyber Resilience Act),

supply chain security (Union Preparedness, EU Regulation 2025/1733 on the security of gas supplies, IMERA - Internal Market Emergency and Resilience Act).



Here you can find a brief overview of the guidelines and requirements set out by the main regulations for the "smart" evolution of the infrastructure: the CER Directive, the DORA regulation and the NIS2 Directive.

The main EU Regulations concerning infrastructure resilience

CER Directive (Critical Entities Resilience)

Passed on 14th December 2022 and transposed in Italy in 2024, the 2022/2557 European Directive aims to ensure the European critical infrastructure security against physical and cyber threats.

Compared to the previous Directive 2008/114/CE of the European Council, the CER broadens the sectors covered, the scope of action - no longer limited to protection alone – and establishes the criteria for designating critical entities at national level, coordinated at the European level.

A minimum perimeter within which to identify critical entities is defined, involving 11 sectors:

Energy

Transport

Banking

Financial markets

Healthcare

Drinking water

Wastewater

Digital infrastructure

Public Administration

Space

Food.

The criteria include the potential impact of the activity or nature of the identified entities on economy and security, the essential nature of the services provided, their interconnection with other sectors, and their transnational relevance.

Entities classified as critical are required to carry out periodic risk assessments, draft and update resilience plans, notify detected incidents, and share relevant information. Moreover, the Directive sets out physical and cybersecurity measures to be implemented, along with monitoring and compliance procedures, and sanctions for non-compliance with its requirements.

DORA Regulation (Digital Operational Resilience Act)

Regulation (EU) 2022/2554 of the European Parliament and the Council dated 14th December 2022 aims to strengthen the information and communication technology (ICT) security of EU financial entities, reinforcing the ability to withstand, respond to and recover from cyber incidents and ICT systems disruptions.

DORA's main area of intervention consists in the definition of technical standards to be implemented by financial institution and their critical technology service suppliers, introducing a harmonised framework for the governance of ICT risk across Member States.

The entities subject to the Regulation are required to classify and record ICT incidents and to report serious ones. Voluntary reporting of significant threats and the development of voluntary mechanisms for exchanging data and information on cyber threats between financial institutions are also encouraged.

Additional obligations are to carry out advanced tests on the ICT systems to assess their robustness and controls of critical ICT services on third-party providers.

The Regulation came into force on 17th January 2023 and apply as of 17th January 2025.

NIS2 Directive (Network and Information Security)

The NIS2 Directive establishes cybersecurity obligations for organisations operating within the European Union (EU), to ensure a high and uniform level of protection across Member States.

This new directive, passed in 2023 and transposed in October 2024, addresses the shortcoming of the 2016 directive by introducing more stringent rules, expanding the number of entities and sectors involved and imposing more severe sanctions in case of non-compliance with its provisions. The NIS2 applies to medium and large businesses operating in strategic areas such as energy, transport, industrial production, water resources management and healthcare, as well as banking, financial institutions and digital service providers. Small businesses may also fall within its scope if they supply companies subject to the directive or operate in critical sectors.

Based on their scale and sector of activity, organisations are classified as "Essential" or "Important". Both must adopt the same security measures, but essential entities are subject to stricter controls and heavier penalties for violations.

From European regulations to national realities

The European Commission's strategic guidelines – together with various financing and innovation support plans, as well as Directives and Regulations on critical infrastructure resilience – outline a common framework of goals and tools for enhancing the development of the EU's infrastructure system. This framework aims to enhance efficiency, sustainability, security and resilience ensuring the continuity of essential services. However, the practical implementation of these guidelines varies from State to State, depending on strategic priorities, the condition of existing infrastructure and the capability to absorb European funds.

To date, one of the main sources of EU funding is the Recovery and Resilience Facility (RRF). Member States have adopted different approaches to strengthen key sectors such as energy, water and transports: some have prioritised digitalisation and ecological transitions, while others have focused on upgrading networks or on water resource management.

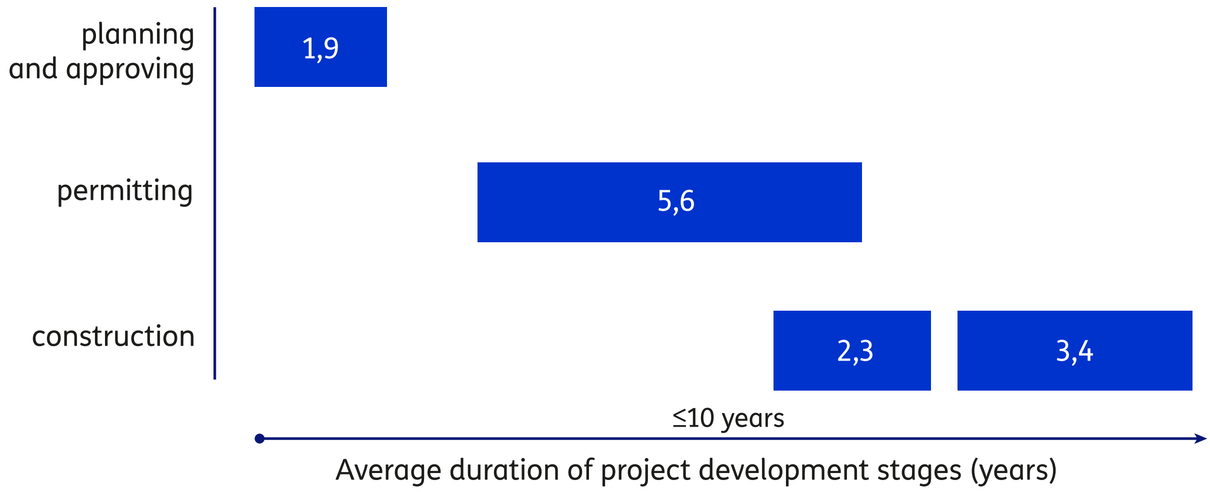
The following comparison presents major infrastructural initiatives in Spain, France, Germany and Italy, along with an in-depth analysis of the UK. This overview shows how each Country interprets and implements the European regulatory framework, highlighting differences in investment priorities and strategic approaches. These variations reflect each Country's unique starting point and the strengths and weaknesses of each national infrastructure system.

A common pattern emerges in all cases examined: substantial resources and ambitious plans often clash with long lead times for project completion, mainly due to bureaucratic delays and administrative complexities in allocating public resources. To address this, some Countries have launched initiatives to streamline processes, such as External Administration in Italy or priority projects of prevailing public interest in Germany. In the UK, following an in-depth assessment by the Office for Value for Money, the Infrastructure and Projects Authority (IPA) was established, to monitor progress of infrastructural projects and reduce the delays which affected major works completion in the past.

An analysis of construction timelines shows that major delays occur during the initial phase, along with the authorisation process, affecting the quality of the outcome. When infrastructure is built after years of waiting, it is more likely to suffer from design obsolescence, an issue which is even more relevant today, given the rapid pace of technological evolution (smart grids, digital twins, storage systems, IoT sensors). Additionally, new sensitivities and needs can change the regulatory framework. Modern infrastructure must be at the very least sustainable, resilient and sovereign, criteria that were not central in the planning decisions made 10-15 years ago.

There is a potential risk that infrastructure designed

The average project implementation timeline: the case of electric grids



Source: ACER calculation based on PCI monitoring data

with today's technologies and standards may be outdated by the time it is build, requiring both immediate updates and structural revisions that could undermine its effectiveness.

This is a key issue to address when redesigning project governance.

More flexible and adaptable processes, interactive assessments and ongoing design updates are essential throughout the project lifecycle. Tools such as digital twins and BIM (Building Information Modelling) enable real-time monitoring and adjustments, thus reducing the risk of prolonged project delays.

It is essential to promote digital platform use and simplify administrative procedures to reduce authorisation delays.

Coordinated governance with a single implementing body clearly defines responsibilities and reduces the risks of litigation.

Through the experience of the PNRR, Italy has already taken significant steps towards modernising the governance of major infrastructure projects. It is essential to ensure that this approach becomes standard practice.

0.9 M **km**
333 DSO and **1** TSO

14 years
age of
transmission network

23 years
distribution network

99%
smart meters share

~12€ billion
allocated for Green
Transition under RRF

-12% river flow
-25% water loss
estimates

56 years
age of dams

1 million
smart meter at
national level

33%
population in
vulnerable areas

22.8€ billion
stanziati fino al 2027

85€ million
needed 2025-2035

20%
high-speed network

1.7% share
of GDP (2023)

10€ billion
allocated for smart
and sustainable
transport under RRF

Spain

Over the past twenty years, Spain has made significant progress in strengthening its infrastructure facilities, with targeted measures in the energy, transport and digital network sectors. These resulted in extended coverage in many areas of the Country that were initially at a significant disadvantage compared to major metropolitan areas and the most developed regions of the Country.

Unlike other States, Spain has focused primarily on the water sector, which faces several challenges. This focus is particularly important given that 33% of the population lives in areas at risk of water shortages. In recent years, river flow has decreased by 12%, while dams have an average age of 56 years. Water networks have an estimated loss rate of around 25%, stressing an urgent need of innovation, as found by several studies (PwC, Seopan and others). One indicator of digital technologies adoption in the sector is the still limited spread of smart meters, despite initial plans for full coverage by 2020. According to the latest data, there are around 1 million meters nationwide, with the highest concentration in the Madrid area.

Current infrastructure programmes aim to achieve structural transformation by making extensive use of European funds, complemented with national resources. Alongside Italy, Spain is one of the main beneficiary of RFF funds for water management projects. In 2023, the Third Cycle Hydrological Plans were approved, i.e. 6,500 measures with a total investment of 22.8 billion up to 2027. However, the allocated resources are insufficient to meet estimates for the 2025-35 period, which amount to 85 billion Euros.

In recent years, Spain has made substantial investments in the energy and transport sectors. Now the country has an extensive and modern electricity grid (around 0.9 M km with a 99% smart meter take-up) and a 20% high-speed network share (AV), among the highest in Europe. Under the Recovery and Resilience Facility (RRF), Spain has allocated around 12 billion Euros to the green energy transition, reaffirming its commitment to a sustainable model, and around 10 billion Euros to sustainable and smart transport projects, a volume of funds second only to Italy.

1.5 M km
138 DSO and **1** TSO

20-50 years
age of
transmission network

17-25 years
distribution network

94%
smart meters share

~9€ billion
allocated for Green
Transition under RRF

-14% river flow
-20% water loss
estimates

60 years
age of dams (2020)

5€ million
smart meter at
national level

12%
population in
vulnerable areas

Plan Eau
2023

about **80€ pro capite**
wastewater collection and reuse

16%
high-speed network

1,7% of GDP
(2023)

Among the largest
RRF shares
for the railway network

France

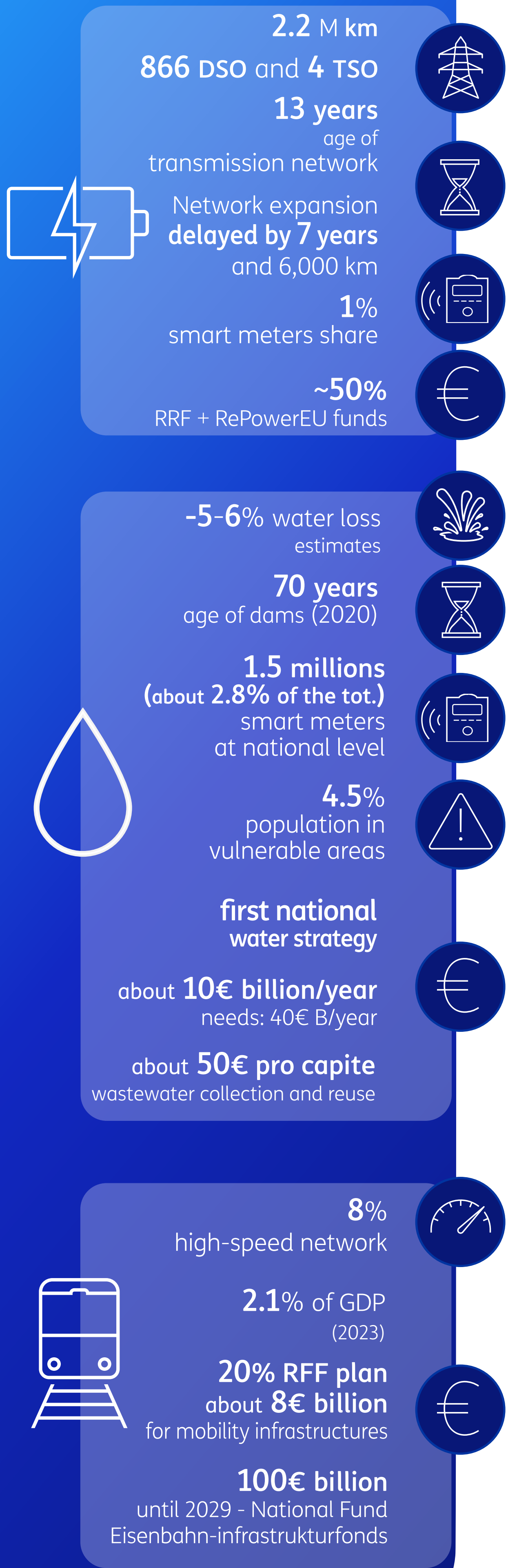
France stands out for its highly centralised approach to infrastructure design and planning. This model enables greater efficiency in authorisation processes and helps reduce ancillary costs, due to more streamlined administrative procedures compared to other European Countries. However, there are some critical challenges, particularly in the transport sector, where railway projects face significant delays. As a result, most RRF funds have been directed towards upgrading railway infrastructure projects (TEN-T) and developing the ERTMS (European Rail Traffic Management System).

Overall, transport spending accounts for 1.7% of GDP and the HS network for 16%.

As to water infrastructure, the "Plan Eau" launched in 2023 aims to strengthen its resilience. However, water losses remain at 20% and 12% of the population resides in shortage risk areas.

Additional risk factors include the advanced age of dams – which in 2020 had reached an average of 60 years – and water smart meter take-up still at 20%, below the European average of 30%, with projection reaching 40% by 2030. Significant investments have been allocated to wastewater acquisition and reuse: around 80 Euros per capita compared to an EU average of 45.

France's electrical grid spans 1.5 million km and is managed by 138 distribution operators (DSOs) and one transmission operator (TSO). The grid is highly digitalised, with a 94% smart meter rate and an energy plan aimed to achieve climate neutrality by 2050, based on a mix of nuclear and renewable sources. The plan identifies an investment need of €100 billion in the 2025-35 period. To date, the RRF funds allocated to Green Transition amount to approx. 9 billion Euros.



Germany

Germany has started an ambitious infrastructure modernisation programme, promoted by the new government. The plan includes increased public spending, the mobilisation of private capital and a reassessment of the State's role in strategic sectors. Its goal is to accelerate implementation timelines by identifying so-called "prevailing public interest projects".

Major efforts are focused on energy and railways, while the water sector – at the hearth of the first national water strategy adopted in 2023 – is less critical compared to other Countries. Water losses are limited to 5-6% and only 4.5% of the population lives in shortage risk areas. However, digitalisation remains limited, with only 2.8% smart meter rate. The first National Water Strategy was adopted in 2023 providing for an investment plan of approximately 10 billion Euros per year, yet no water projects have been submitted under the RRF. Regarding wastewater reuse, the average investment stands at 50 Euros per capita, slightly above the EU average of 45. The estimated requirement for the water sector is of approximately 40 billion Euros per year.

Germany has the most extensive electrical grid among the Countries examined (2.2 million km), grid managed by 866 distribution operators (DSOs) and 4 transmission operators (TSOs). The transmission network has an average age of 13 years, making it relatively newer compared to other Countries. However, its expansion lags behind by about 7 years (6,000 km). System digitalisation remains limited, with smart meters accounting for only 1% of the total. Still, the German RRF budget for a green transition has been significantly boosted by the REPowerEU programme, attaining around 50% of the total. In this way, Germany aims to achieve net-zero emissions by 2035, well ahead of the 2050 target, with significant investments in energy storage systems to address challenges stemming from the Russian-Ukrainian conflict.

In the transport sector, expenditure amounts to 2.1% of GDP. The HS network is underdeveloped, accounting for only 8% of the total, and is considered a highly critical area. Around 20% of the German RRF plan (~€8 billion) has been allocated for developing mobility infrastructure. Additionally, the national Eisenbahn-Infrastrukturfonds has earmarked 100 billion Euros to strengthen railway networks by 2029. To promote alternative sustainable mobility models, investments are planned to expand both the electrical and hydrogen charging networks, with particular attention to commercial vehicles.

1.4 M km
123 DSO and 1 TSO

100% smart meters share

~28€ billion allocated for Green Transition under RRF

over 2€ billion Terna's plan 2025-2034

-40% water loss

up to-50% in some southern areas

67 years age of dams

25 years age of meters

3.5 millions smart meters at national level

31% population in vulnerable areas

about 20€ pro capite wastewater collection and reuse

4.4% high-speed network

1.5% of GDP (2023)

34€ billion allocated for smart and sustainable transport under RRF

Italy

Italy holds a unique position within the European landscape: it is the Country which benefitted the most from the Recovery and Resilience Facility Fund, with €34 billion allocated to transports and around 28 billion to Green Transition. Alongside Spain, it is also the main beneficiary of RFF funds for water management. However, Italy faces bureaucratic delays and long completion times for infrastructure facilities.

Water infrastructure is in particularly critical conditions: losses amount to 40%, the average age of dams reaches up to 67 years and smart meter take-up is a mere 17%. Per capita investment in wastewater reuse is significantly below the European average: 20 Euros compared to 45 across the EU. Additionally, very long completion times – 6 years for water networks – further exacerbate water shortage risks, which affect 31% of the population.

In contrast, the electrical grid is in a more advanced state, with a strong focus on infrastructure digitalisation: smart meter take-up may have reached 100%, the highest rate in Europe. For the decade 2025–2034, Terna submitted a development plan with €23 billion investments, in line with the goals of the Piano Nazionale Integrato Energia e Clima (PNIEC). Major initiatives aim to strengthen the national transmission network, integrate production from renewable sources, increase cross-country interconnections to enhance energy security, improve resilience through the development of storage systems. One of the most significant challenges is reinforcing the connection between the South of the Country – which has the greatest potential for renewable energy production – with the more industrialised North, which in turn has the greatest energy demand.

In the transport sector, infrastructure spending amounts to 1.5% of GDP. Italy has received the highest rate of RRF funds in absolute value, with the majority allocated to railway infrastructure development, within which high-speed networks remain limited (4.4%). Still, work completion is slow: 13 years for railways infrastructure, 6 years for roads and motorways and 5 years for ports.

United Kingdom

In a global context marked by energy transition, technological competition and geopolitical risks, in 2025 the UK launched "UK Infrastructure: A 10 Year Strategy" – a long-term plan that breaks from the fragmented approaches of the past. Its goal is to transform the economic and social infrastructure into strategic assets supporting growth, resilience and sustainability.

The strategy is backed by a plan worth over £725 billion covering transports, energy, water, digital and social infrastructure such as schools and healthcare. Through this initiative, the UK aims to become a "clean energy superpower" and achieve net-zero emissions. Targeted investments focus on bridging the digital divide with technologies such as optical fibre and 5G, supporting emerging sectors including green tech, AI and biotech, and strengthening railway and digital networks.

Project Governance is one of the strategy's most innovative elements. Following an in-depth assessment of the challenges faced by major works of the past, the UK established a dedicated body – the Infrastructure and Projects Authority (IPA) – to oversee over 780 projects, accelerate authorisation processes and implementation timelines, to prevent the excessive delays that affected previous projects' completion.

A 10 Year Strategy

Transforming economic and social infrastructure for **growth, resilience** and **sustainability**

>£ **725 billions**
transport, water, energy, digital, schools and healthcare

clean energy superpower and **net zero**

better road and **rail connections** between regions

5G e **optical fiber** to bridge the **digital divide**

support for **emerging sectors** (green technologies, AI, biotech)

simplification of the process

over **780 projects** monitored by **Infrastructure and Projects Authority** (IPA)
cost management and reduction of bureaucratic obstacles

Part Three

Market and **benefits**

CHAPTER 6: Infrastructure monitoring: markets

Infrastructure monitoring

The infrastructure market is undergoing a transformation phase marked by an increasing integration of private capitals to complement traditional public financing. This combination – which results in public-private partnership (PPP) models – allows risk-sharing among all parties involved, optimise resource allocation and bring private sector management expertise into the system, while still ensuring public guarantees and protections.

In Italy, Terna and DSO are among the main actors of this process in the power network sector. This evolution has been also highlighted by:

- Blackrock, that – based on an analysis by the Global Infrastructure Hub[68] – identified infrastructures as a strategic asset for the next 15 years, with an extimated global demand of 68,000 billion dollars by 2040[69].
- EY, which in its 2025 Infrastructure Barometer highlights a growing investor confidence, 36% of which allocated more than 30% of their portfolio to greenfield projects.

This accelerates work completion, but the increasing complexity and the need to ensure resilience and sustainability require a qualitative leap in the development of management and control tools. In other terms, the importance of smart monitoring tools is growing, both for infrastructure (plants, works, buildings, distribution networks), and for demand (consumption, usage behaviour). These tools close the information cycle, analyse energy flows, identify inefficiencies and enable demand-response strategies, facilitating virtuous behaviour and reducing waste.

In fact, the more the ability to collect and analyse real-time data grows by integrating detection technologies, computational power and predictive algorithms, the more infrastructures become dynamic and flexible platforms, with tools detecting potential disruptions in advance and adapting to potential shocks, as well as activating or introducing "greener" behaviour models.

In this context, smart monitoring is not just a mere technological tool but it becomes a true strategic factor making infrastructure efficient, resilient and sustainable and helping to extent its life cycle.

Between 2025 and 2029, the energy, water network and civil infrastructure monitoring sectors should grow on average between 10% and 15% per year, reaching globally over 100 billion Euros and in Europe over 26 billion by 2029. In Italy, the average annual growth rate of the energy and civil infrastructure monitoring sectors is among the highest in Europe (+15% and +9% respectively).

The civil infrastructure monitoring market

The civil infrastructure sector, which includes roads, bridges, schools, hospitals and urban transport networks, is driven by government plans - such as NRRP in Italy and the Build Back Better Plan in the United States – that allocate large funds to modernise, make resilient and sustain the works. This dynamic is reflected in market data: in 2025, the public work sector in Italy recorded a 16% growth, while residential construction contracted due to the withdrawal of tax incentives.

The acceleration of investments in this sector makes the management and maintenance of infrastructure even more essential, increasing the importance of monitoring tools such as Structural Health Monitoring. These systems are based on advanced sensor technologies, integrated with smart algorithms, to assess the structures' state of health. This enable to detect early on damages or deteriorations, reducing the risk of serious subsidence and optimising maintenance costs, with direct effects on the infrastructure life cycle and the protection of public and private investments.

The importance of SHM systems is rapidly increasing, since:

- these systems have a strategic role for the success of infrastructural projects, adapting their applications to structure complexity. This is why their implementation is needed throughout a work life-cycle (before, during and after construction), and in monitoring the structures' conservation state.
- SHM systems, born in the aerospace and aeronautical fields, have been taken up in other sectors, as in civil infrastructures (dams, tunnels, bridges, buildings, stadiums, etc.) and are also used in the energy, mineral industry, industrial machinery, transport (automotive and railways) and maritime sectors.

The analysis of the structural monitoring systems market can be carried out following two different perspectives:

- from the supply side, two leading segments are to be considered: available technologies (hardware) and services supplied also through software solutions;
- from the demand side, different application sectors – such as civil infrastructure, energy, transport and industry – and/or geographic areas can be identified. This segmentation help highlighting the differences of adoption among industries and regional markets.

According to MarketsandMarkets, the monitoring infrastructure global market reached a value of 2.3 billion Euros in 2024 and a significant growth is expected: from around 2.5 billion in 2025 up to 3.7 billion in 2029, with a +10.1% average annual rate. This dynamic reflects a growing awareness of the importance of predictive maintenance and structural safety, especially in contexts – such as in Europe – where many infrastructures exceeded their useful life.

Apart for growth, the data also show another dynamic: the transformation of the market shifting progressively from hardware to software and services solutions. The hardware share – physical sensors and devices – is expected to decline from 58.6% of total revenues in 2020 to 52.7% in 2028. Meanwhile, software and services – analyses platforms, AI-based cloud solutions and applications – will grow up to 47.3% of the market. This shifting marks the transition towards digital and integrated solutions, enabling predictive analyses and remote management, key elements for safer and more efficient infrastructures.

In Europe, Germany accounts for 26% of market revenues in 2025 and a +10% expected growth. Italy accounts for 12% of the market, with a +9.2% estimated growth. In absolute terms, the Italian market should go from 91 million Euros in 2025 to 129 million in 2029.

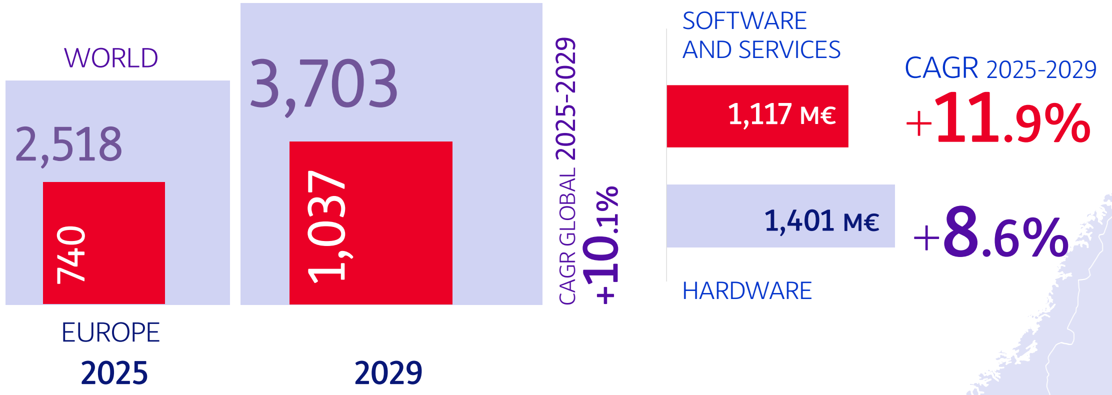
Another valuable perspective is the distinction between wired and wireless systems.

Wired system monitoring is used to assess several structures, such as buildings, tunnels, bridges and dams. Their advantages, including reliable connections and unlimited data transfer, are driving market growth. However, the wireless technology market is expected to register a higher average annual growth rate over the forecast period, owing to cost savings from eliminating cables, which reduces installation and maintenance expenses.

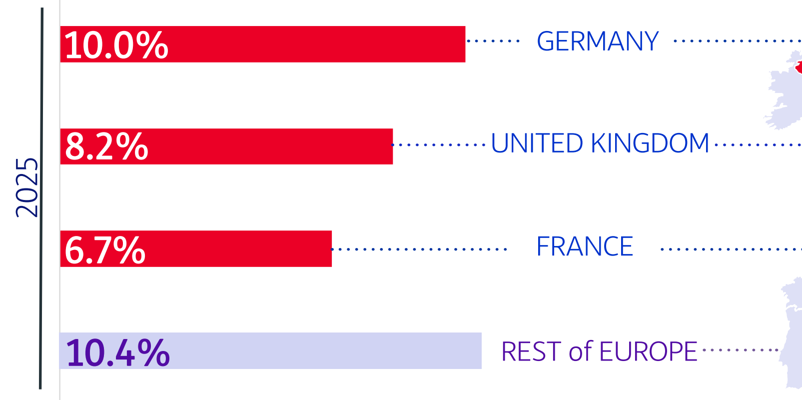
Wireless systems also offer greater flexibility, as the different sensors used in wireless structural monitoring communicate via wireless transmission, making it easier to upgrade, add, move or replace sensors after the initial deployment. A progressive transition from wired to wireless systems, passing from 26.3% to 31.9% in the same period, is highlighted.

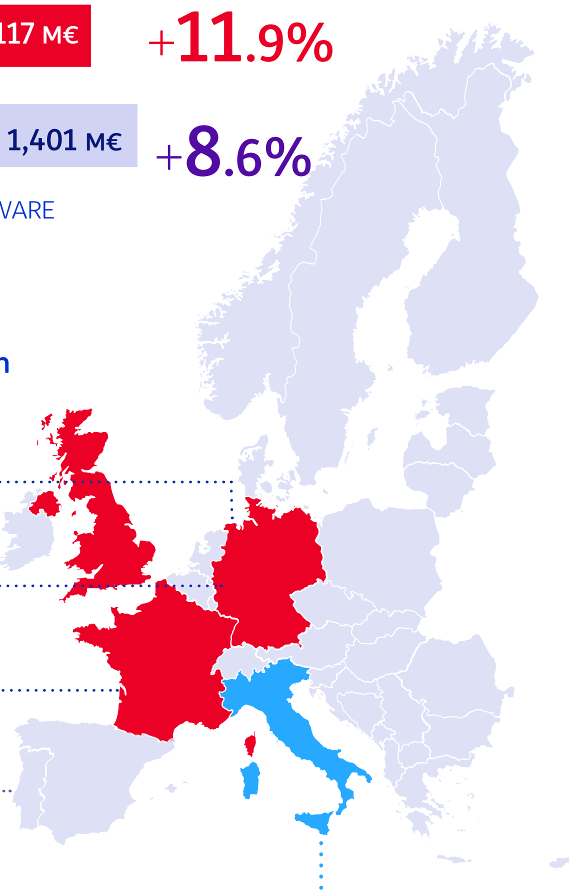
Civil infrastructure

Connected infrastructure monitoring market (M€)



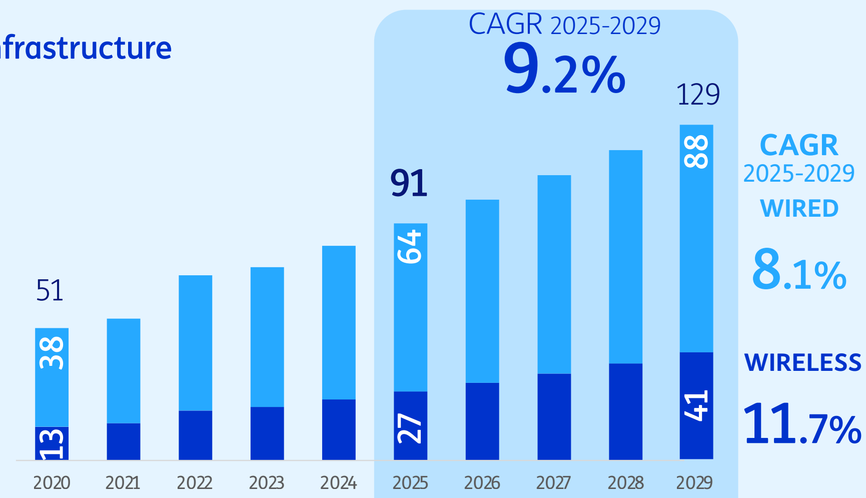
Connected infrastructure monitoring market in the main European countries (M€)





The Italian Connected Infrastructure Monitoring Market (M€)

The Italian infrastructure monitoring market to grow from 91 to 129 million Euros by 2029. The Wired segment will maintain a 68% share while the wireless segment, driven by IoT and cloud, is to grow more rapidly (CAGR 11.7%). The trend favours efficiency, scalability and sustainability for smart and resilient infrastructure.



Source: "Structural Health Monitoring Market" - MarketsandMarkets 2024

Electrical Infrastructures Monitoring market

In a context increasingly oriented towards more sustainable and resilient energy systems, power networks become essential. The European Commission has estimated an investment need of over 1,200 billion Euros by 2040, including 730 billion for distribution and 472 billion for transmission. In Italy, Terna has planned investments for 23 billion Euros in the ten-year period 2025-2034, while major DSOs (distribution operators) have already exceeded 4.8 billion Euros expenditure in 2024, and estimates more than 4 billion Euros per year for the two-year period 2025-2026.

These investments are essential to transform power networks into smart grids capable to integrate renewable energy sources, which are “intermittent” and “non-programmable” because they depend on natural conditions. The transformation process is driven by progressive network digitalisation and the development of Energy Management Systems (EMS). Similar to SHM for civil infrastructures, EMS act as a key tool to optimise, control and manage energy distribution, improving efficiency and enabling the integration of new renewable plants. This allows significant cost savings and reduces environmental impact.

EMS integrate hardware, software and services and market analyses.

The global EMS market includes (hardware and software) service-designed technologies and solutions (optimisation of energy consumption, distribution and storage in residential, commercial and industrial sectors, etc.).

The monitoring system global market for connected power networks is experiencing an extraordinary growth. According to the latest estimates, global revenues should raise from 44 billion Euros in 2025 to 76 billion in 2029, with an annual average growth rate of +14.5%.

The market is divided into three main categories, software, hardware and services, each playing a key role in optimising consumption, reducing operational costs and achieving sustainability objectives.

- Hardware includes essential devices such as smart meters, sensors and storage systems, essential to collect and transmit information over the network.
- Software is dedicated to advanced data analysis, automation and real-time monitoring, enabling rapid and smart decisions.
- Finally, services offer consulting, implementation and ongoing support, so that solutions can be integrated and operating over time.
- The integration of these three components forms the backbone of modern energy management strategies, addressing the growing demand for efficiency, legal compliance and sustainability across all sectors.

Revenues from hardware account for around 60% of the global market. The main growth drivers are network innovations that are accelerating the adoption of smart technologies to comply with increasing stringent regulations aimed at reducing emissions and improving sustainability. Hardware revenue growth, which faces several obstacles (high initial costs, complexity of integration with existing systems, need for specialised skills and regulatory differences across regions) should increase on average by 14.2% per year in the period 2025-2029.

According to estimates, the software segment of the global EMS market grows at an even faster rate (on average, +15.3% per year in the period 2025-29). This segment, essential to enable entities to monitor, analyse and optimise energy consumption, accounts for around 25-26% of the market. Revenues are generated by solutions such as analysis platforms, demand response tools, billing systems, software of energy modelling, applications for emission reporting and forecast tools.

Services is the smallest segment (about 14-15% of the market), with an estimated growth of around 14.7%.

At the European level, Germany is the most important market (32%) while Italy, despite a 6% share, is the country with the most significant growth forecast (+15%), an indicator attesting the important transformation underway in our country. In absolute terms, the Italian market goes from 733 million Euros in 2025 to 1.29 billion in 2029. The leading sectors involved are:

Power & Energy: 36.1%

Telecom & IT: 23%

Manufacturing: 14.8%

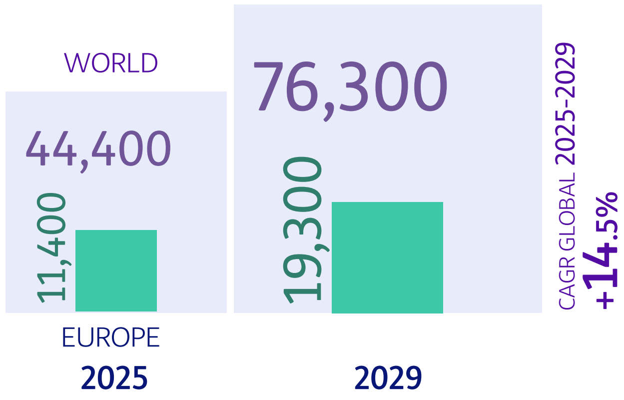
Residential & Commercial: 9.8%

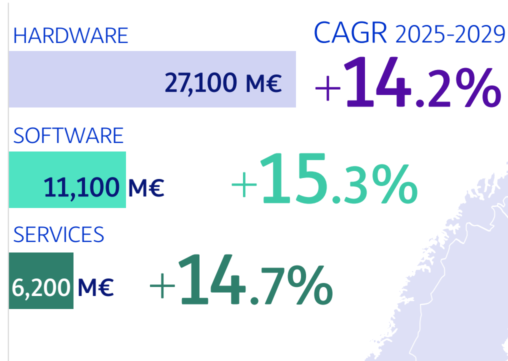
The data show how monitoring is essential both for electrical distribution, and for industrial and digital sectors ad high energy intensity.

Future prospectives are very positive: the integration with Industry 4.0, smart grid, IoT, artificial intelligence and big data analysis technologies will make EMS increasingly sophisticated and capable of managing energy in real-time. The transition towards decentralised energy systems and the growing demand for sustainable solutions, especially in emerging markets, will further enhance the sector.

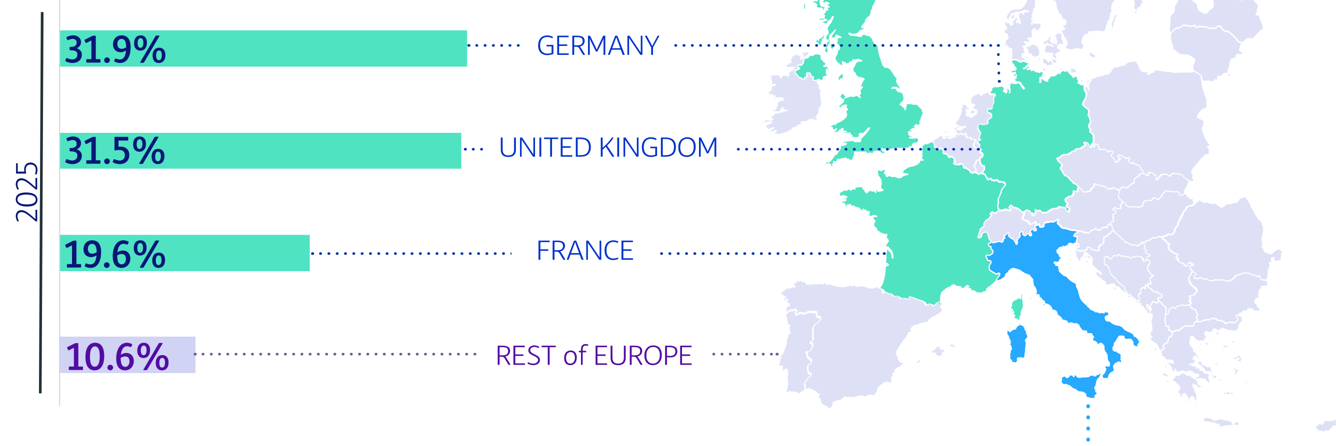
Electrical infrastructure

Electrical infrastructure monitoring market (M€)



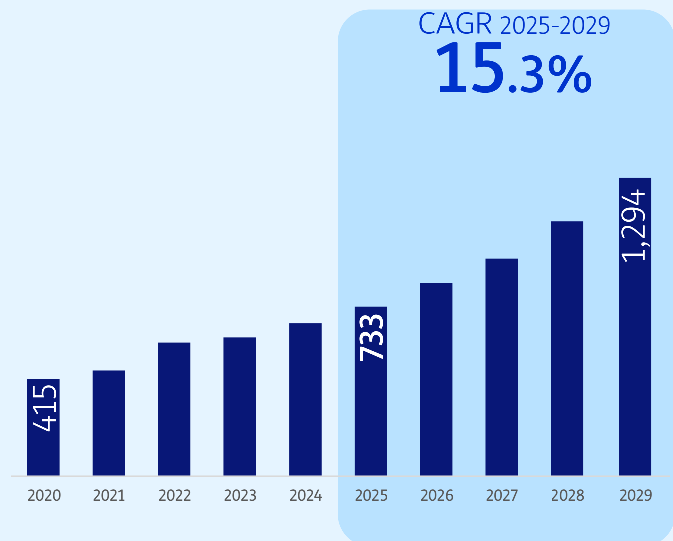


Electrical infrastructure monitoring market in the main European countries (M€)



The Italian electricity grid monitoring market e (M€)

The Italian electricity grid monitoring market is growing rapidly. Power & Energy dominate (35-37%), followed by Telecom & IT and Manufacturing (~15%). Digitalisation, IoT, cybersecurity and predictive analysis drive the energy transition towards sustainability and CO2 reduction, also involving minor sectors.



Fonte: "Structural Health Monitoring Market" - MarketsandMarkets 2024

Water infrastructure monitoring market

Water sector, although less visible than the energy sector, is equally essential, if not more relevant, for economic and social stability. In a context of ecological transition and climate stress, water scarcity represents an increasingly positive risk for our societies and the supply distribution networks face challenges related to plant aging, dispersion and resource sustainable management. Digitalisation and smart monitoring investments are no longer options, but strategic levers for network update and are focused on control, automation and smart management technologies, with the aim to reduce losses, improve water quality and ensure water safety.

The National Recovery and Resilience Plan (NRRP) allocated over 4 billion Euros for interventions in the water sector, with a specific focus on network digitalisation and the implementation of advanced monitoring systems. Among the strategic goals are water loss reduction, resource protection and plant management efficiency[70].

The NRRP envisages the introduction of innovative technologies to control critical nodes and vulnerable areas of the network, with the aim to transform legacy networks into smart networks capable to collect and analyse real-time data on water flow, pressure and quality. This approach is essential to reduce waste and improve the resilience of the national water system[71].

According to forecasts, the connected water network monitoring market could grow at an average annual rate of 11.9% in the period 2025-2029, going from 18 to 25 billion Euros globally. This dynamic above all reflects the need to renew obsolete infrastructure and the strategic goal to reduce unaccounted water losses to preserve water resources.

Distinguishing between hardware devices (mainly meters) and software solutions and services, the latter show higher growth dynamics (+14.1%), while sensor components record the lowest growth. Actually, water meters include AMR (Automatic Meter Reading) and AMI (Advanced Metering Infrastructure) devices. AMR meters, implemented in the system for quite some time, represent a larger market segment compared to AMIs, but the trend is due to change. AMI meters – which feature faster communication capabilities and decreasing costs – will grow faster than in the past as more suited for smart network management needs.

Smart Water Management (SWM) solutions are divided into several very different categories, among which:

- corporate asset management,
- data analysis and management,
- security,
- smart irrigation management,
- APM (Asset Performance Management),
- mobile workforce management (MWM),
- network management,
- CIS (Customer Information System) and billing,
- loss detection and other applications.

Among these typologies, corporate asset management accounts for the largest share of the SWM solution market, enhanced by the adoption of real-time monitoring technologies and predictive maintenance, essential tools to ensure continuity and reduce operational costs. Predictive maintenance, in particular, should have a rapid growth due to the increasing need of operational efficiency and disruption prevention, a very critical aspect in this type of infrastructures. On the other hand, data analysis and management should register the highest growth rate. This is because innovation in the sector– compared with the past – will lead to a significant increase in the amount of data collected, enabling the development of decision-making systems to identify the most effective solutions in terms of consumption management.

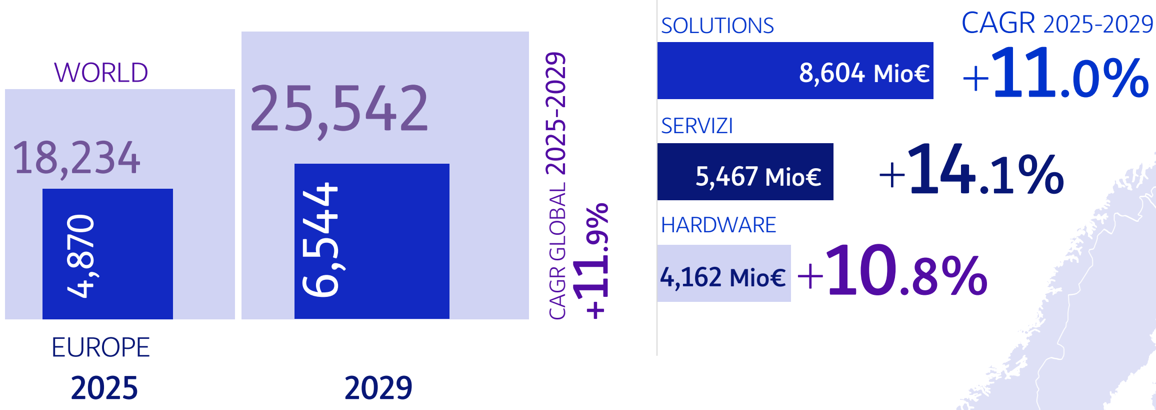
SWM services are divided into three large areas: professional, support/maintenance and management services. The first typology includes consulting, integration and implementation to plan, tailor and initiate smart water systems. Support/maintenance services are referred to the activities needed to ensure the system's optimal functioning, continuity and security over time, while managed services enable a complete view of the system to ensure its full governance.

The whole service segment presents the most sustained growth in the relevant period (+14.1%). This dynamic is driven above all by the increasing need to update and maintain current solutions and by the expansion of modernisation projects in different regional areas. Nowadays, utilities are also adopting managed services for seamless operations. Moreover, managed services help utilities to better focus on their main operational needs.

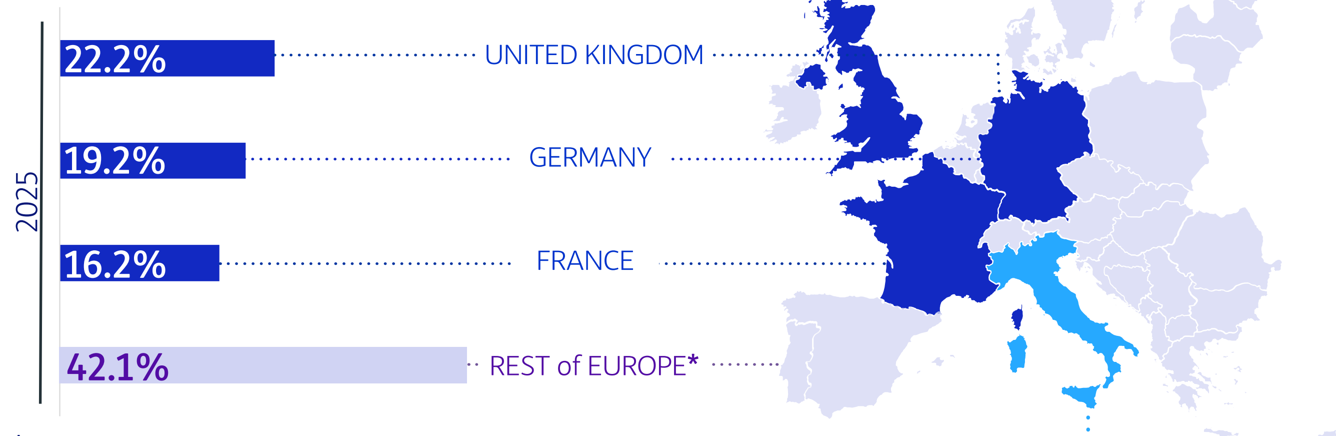
Europe represents a relevant share of the global market. European utilities show some proactivity and a progressive implementation and modernisation of water infrastructure. United Kingdom represents the most important market of the area, with a 22% share in 2025, while France shows a more rapid growth (+11.4% of average annual growth in the relevant period). Italy, albeit with an extended and outdated water network, has still considerable potential for improving, especially in terms of digitalisation and smart metering.

Water infrastructure

Water infrastructure monitoring market (M€)



Water infrastructure monitoring market in the main European countries (M€)



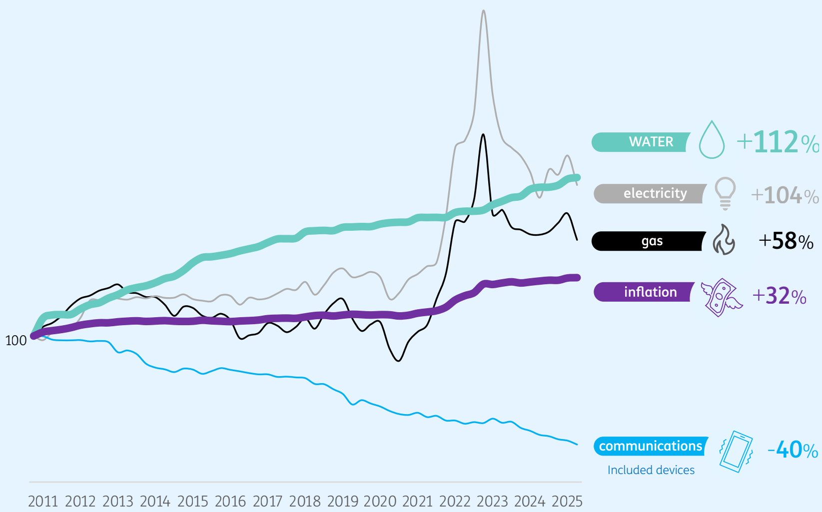
*The rest of Europe includes Italy, Spain, the Czech Republic, Poland, and Switzerland.

Source: "Structural Health Monitoring Market" - MarketsandMarkets 2024

Price trend

2010 index number = 100
Graph on logaritmic scale

The price of water is more than doubled since 2010, highlighting rising management costs and the progressive scarcity of water resources.



Source: "Structural Health Monitoring Market" - MarketsandMarkets 2024

Smart Energy

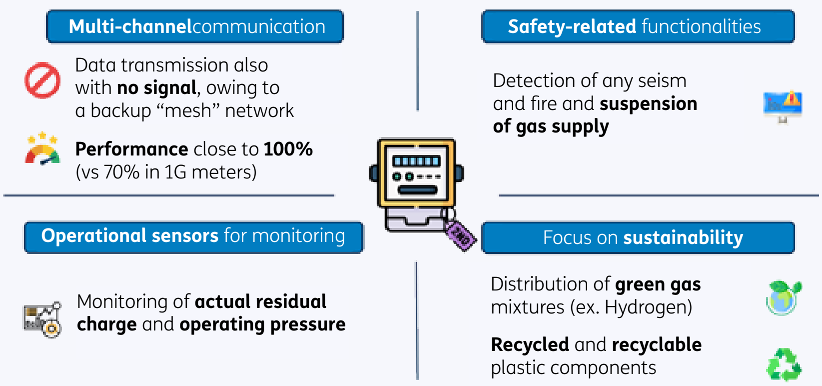
POLIMI SCHOOL OF MANAGEMENT | osservatori.net digital innovation

The digitalisation of the Utility sector is accelerating, owing to the adoption of technologies promoting innovation and greater efficiency. This trend is confirmed also at Italian level, looking at the trend of the ICT budget of companies in this sector and especially the share allocated to digitalisation compared to revenues[1], growing from 2.1% in 2019 to 2.8% in 2023, up to 2.9% in 2024, a current value higher than that recorded in other sectors, such as industry (2.2% in 2024) and services (2.7%). The constant growth of the share of revenues allocated to digitalisation confirms the strategic importance of these investments for the future of utilities.

This is why it is essential to identify the main technological innovations adopted by the companies of the sector. To this aim, the Osservatorio carried out an analysis at international level to record the innovative enabling technologies used in the most recent digitalisation projects. Out of a sample of 282 initiatives, 28% is based on IoT technologies, 20% on Artificial Intelligence and 18% on Data Analytics solutions. Other emerging technologies follow, among which drones, satellites, Digital Twins and Blockchain. In most projects, technologies are implemented together, with spread of IoT-Data Analytics and IoT-AI combinations. This highlights the increasingly central role of IoT in the collection of data, which are subsequently enhanced trough advanced analysis tools or AI algorithms, allowing to extract information of greater value.

The temporal evolution analysis of the Smart Utility projects highlights a significant growth starting from 2023: the quota di initiatives is passata from 14% in 2022 to 30% in 2023, up to 32% in 2024. In terms of sectors involved, 57% of the projects is related to the electric sector, 25% to water sector and 18% to gas. By analysing these fields, we can observe how the applied technologies are distributed along the value chain and the features and interventions they enable.
In the electric sector, innovations are concentrated in the phases of production from renewable and non- renewable sources, energy transmission and distribution. The main technologies are IoT, drones, AI and Data Analytics. These solutions allow network inspections in difficult areas, constant monitoring of operating conditions, timely malfunction detections and predictive maintenance.
In the water sector, these technologies are applied mainly in the extraction and distribution phases. IoT is the most used, followed by satellite technology, AI and Data Analytics. The more widespread intervention is leak detection, enabled by AI, sensors and satellite images, which analyse pressure variations of the water and humidity of the soil to detect anomalies. Another key application is the monitoring of the quality of water, acquiring real-time data on parameters such as pH, chlorine, turbidity and contaminants. Moreover, infrastructure monitoring and malfunction detection solutions are adopted.

1 Source: Osservatorio Startup Thinking, 141 respondents, 2024



Smart Metering gas

le caratteristiche del nuovo contatore 2G

Source: Osservatorio Digirtal Innovation - Politecnico di Milano (www.osservatori.net)

CENTRO STUDI TIM

In the gas sector, the projects are equally distributed between upstream (exploration and production), midstream (processing, transport and storage) and downstream (distribution and export). AI is the most used technology, followed by IoT, robotics and drones. The main interventions concern leak detection, with AI algorithms capable of identifying data anomalies, inspection via drones and robots to reduce the risks of manual assessments, predictive maintenance to prevent malfunctions and optimise costs and cybersecurity to ensure the safety of the network.
In this innovation scenario, Smart Metering represents one of the most relevant components of the market, owing to several roll-out plans implemented in recent years to replace traditional meters with new generation connected devices.
In Europe, smart meter spread varies significantly from State to State: Belgium and Germany present a still limited roll-out (less than 20%), Portugal and the United Kingdom are halfway through the replacement process (around 50%), France and The Netherlands have already reached an adoption around 90%, while in Italy the installation of first generation meters has been completed for several years and a share of 1.4 million second generation meters has been achieved, with an incidence of 75%. However, the meter degree of spread and replacement is not the only evaluation parameter: in fact, it is essential to consider also the advanced features offered by smart meters. Our Country, having started early, has less features compared to other Countries which started later. To face this challenge, the Italian market is trying to make its own offer for 2G meters evolve: if a 24-30-hour delay persists today in sending data from distributors to information systems ("chain 1"), new offers related to "chain 2" appear on the market. These are specific modules and sensors which acquire data directly from domestic users, making them available to utilities and enabling the companies to activate tailored offers based on real-time monitoring of energy consumption. New solutions involving the integration with AI algorithms also advance, allowing to analyse and foresee consumption with the highest accuracy, up to the identification of the energetic behaviour of single devices.

In the gas sector, the average roll-out at European level has reached 43%[2], with Italy, France and The Netherlands among the more active States. In Italy, the meter industry park is fully smart, while for domestic users the spread reached 90%, with point-point (59%) and multi-point (41%) technologies. In this area too, work is underway on second generation meters (see Figure 1), with installations already started. These devices can communicate on multiple channels, combining primary networks (for example, NB-IoT and LoRaWAN) with a "mesh" backup network, allowing data transmission even in the absence of a signal and recording performances near 100% (against 70% by the first-generation meters). Moreover, these meters are equipped with features and algorithms related to safety, as well as operating sensors: the former enable to detect any seisms and fires and to suspend gas supply, while the latter monitor the actual remaining power of the meter and the operating pressure.

As to the water sector, albeit installations are still limited, the market is booming. In Europe, the sector is worth 1.3 billion dollars, with a 49%[3] roll-out. In Italy there are 4 million smart meters installed (19% of the total),of which 500,000 in 2024, with an increase of 14% compared to the previous year[4]. It is a fast-moving sector bringing a series of benefits ranging from remote meter reading to a greater billing accuracy, as well as fraud and pipe malfunction detection. The Osservatorio has quantified the environmental benefits by theorising different roll-out scenarios with 160,000, 3.5 and 17.5 million meters installed (equal to the totality of meters on the Italian territory). Also referring to the three scenarios, the quantity of water saved goes from 2.1 to 63.6 to 453.5 million m3/year, corresponding respectively to a saving of 3.7%, 5.2% and 7.4% compared to a no-smart metering scenario.

2 Source: Berg Insight, 2024
3 Source: Precedence Research, 2024
4 Source: Analisi dell'ufficio studi di MeteRSit, Gruppo SIT, 2023

Smart Road

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The European strategy to achieve the mobility objectives of efficiency, security and sustainability also encompasses Smart Roads. Their growing importance lies in the ability to collect large amounts of data from connected vehicles and smart infrastructure, paving the way to the provision of several innovative services. In fact, 2024 stays a significant year for these initiatives, both at national and international level. The Osservatorio started a worldwide recording of 166 projects from 2017 to 2024[1], registering an ongoing proliferation of new initiatives. Specifically, 46 projects were started in 2024, with an increase compared to 44 in 2023 and 28 in 2022.

The main initiative objectives concern road safety, greater driver comfort, traffic flow optimisation, the ability to optimise road infrastructure maintenance and pollution reduction. In Italy there are 21 initiatives activated in the three-period 2022-2024 only (see Figure 1), as proof of the commitment and interest of the Country on this front. Recent virtuous examples are:

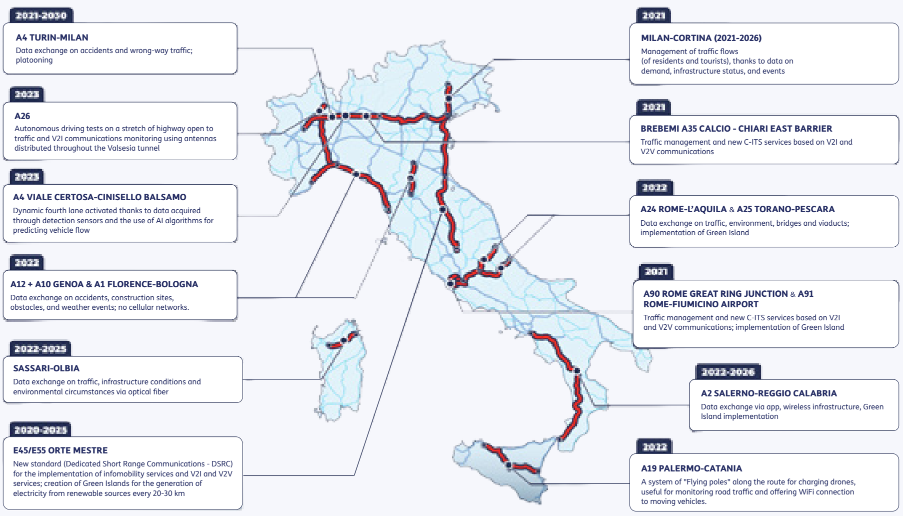
A7 Milano-Serravalle, with a project transforming the whole route in Smart Road by 2026, to improve safety and traffic management through digital technologies for real-time monitoring, incident detection and vehicle-infrastructure communication;

A32, along which in 2024 a 5G-enabled digital corridor near the Frejus tunnel has been opened, aiming to improve the connectivity and safety of the Turin-Lyon axis, to support a connected and autonomous mobility.

A2, where in 2024 the Montalto Uffugo (CS) Green Island has been completed, one of the infrastructures symbol of the Anas Smart Road programme, whose total investments account for around 1 billion Euros and of which a first experimental phase is still ongoing.

The Osservatorio analysed the services of 166 Smart Road projects recorded at international level, classifying them based on three levels of maturity. The fist level includes basic services such as informative services for sending users real-time push notifications, present in most of the projects (54%). The second level is composed by more personalised and adaptive services, such as assisted driving systems (37%), charging for electric vehicles (14%) and integrated mobility (14%) for a safer and fluid driving experience. The third level concerns advanced services such as the performance analysis of the Connected and Autonomous Vehicles (CAV) and the use of cloud platforms to centrally coordinate road flows, acting beforehand to reduce the risk of collisions. Even though this service typology shows a discrete level of spread (39%), it is often present only in trials and pilot projects. In the third level there are also clean energy generation and storage services to power smart lighting systems or charging stations for electric vehicles, still not widespread within the initiatives (1%).

The services enabled by Smart Road projects will be further strengthened through two increasingly used tools: the integration of geospatial data, coming from satellites, and their reprocessing through AI algorithms. In future, we are likely to see increased partnerships between public and private entities, to better integrate information coming from vehicles and infrastructures with satellite and Artificial Intelligence data, accelerating innovation and sustainability in the mobility sector.



Smart Road

the main trials active in Italy

Source: Osservatorio Digirtal Innovation - Politecnico di Milano (www.osservatori.net)

CHAPTER 7: Economic benefits

Main reasons for adopting smart solutions

As shown in the previous chapters, the adoption and usage of SHM systems is generating numerous advantages. Some of these benefits are immediately evident and measurable, others are more generic, linked to the achievement of the 2030 strategy ESG goals. This chapter is to explore the multiple repercussions connected to the spread of SHM technologies, analysing their operational, economic and social impact.

Civil infrastructures

Smart monitoring adoption in civil infrastructures is supported by technical, economic and social reasons:

- **Risk reduction and increase in safety**: continuous monitoring enables to identify construction defects and progressive deterioration, reducing uncertainty and enabling decisions based on objective data[72]. Safety is one of the main benefits of infrastructure monitoring. By identifying problems beforehand, it is possible to avoid incidents and ensure users' and workers' safety. An efficient monitoring system enables to detect structural or environmental changes that could jeopardise infrastructure integrity, allowing preventive measures to be taken to avoid risky situations.
- **Performance enhancement:** through continuous monitoring, it is possible to optimise infrastructure performance, improving its operational efficiency and reducing long-term maintenance costs. For example, in transport systems, monitoring can allow a more efficient traffic management, reducing waiting times and improving quality of service. Moreover, energy infrastructures can benefit from a continuous monitoring to ensure a stable and reliable energy distribution.
- **Predictive maintenance**: shifting from a "time-scheduled" to a "condition-based" strategy, optimising costs and times[73].
- **Early detection of problems**: monitoring can identify anomalies and structural defects in the early phases, allowing timely interventions and reducing the risk of catastrophic disruptions. For example, bridge cracks can be detected and repaired before they widen and compromise structure stability. This early detection prevents incidents and reduces reparation costs, addressing problems before they worsen.
- **Useful life extension**: studies show that the SHM installation on bridges eligible for replacement may reduce overall costs by 30%, avoiding

unnecessary interventions[74].

- **Sustainability**: smart monitoring reduces resource waste, avoids untimely demolitions and supports asset management strategies.

- **Social impact:** apart from technical benefits, monitoring conveys a reliabile and "high-tech" image, reassuring public opinion on the safety of the infrastructure.

Applications and case studies

Among the most emblematic cases there is the San Giorgio Bridge in Genoa, equipped with a monitoring system based on optical fibre sensors and advanced algorithm analysis. This system enables to detect real-time strains, vibrations and thermic variations, ensuring the safety of the work and providing useful data for research[75].

Similarly, several Alpine tunnels, such as Frejus and Monte Bianco, are monitored by distributed sensor networks, capable of detecting displacements, pressures and environmental variations. These systems enable to prevent structural failure and plan targeted interventions[76].

Electrical networks

Modern societies are heavily dependent on electricity, and its lack may cause serious inconveniences. According to data from the U.S. Energy Information Administration (EIA), in 2020 U.S. customers experienced current outages for over eight hours on average, the highest value since the body started collecting data on service continuity[77]. The data was affected by exceptional events such as hurricanes and storms, but even excluding these occurrences, on average, annual outages are around two hours.

In Italy, outages are monitored by ARERA. The average duration of long no notice low voltage (LV) outages[78] per user (SAIDI[79]) went from 99 minutes in 2023 to 76 minutes in 2024[80] (in 2022 they lasted 75 minutes/LV user). The performance duration improvement in 2024 is in part associated to minor impact of extreme meteorological events (floods, windstorms and heat waves)[81]. Considering total long outages[82], including the scheduled ones, LV customers registered an average duration of 185 minutes in 2023, reduced to 163 minutes in 2024. The total number of short and long outages went from 4.88 year per LV user[83] in 2023 to 5.13 in 2024. For many it is still too much, and the electricity companies are constantly looking for solutions to reduce both the blackout number and duration.

In calculating these values, the following are deduced: outages originating over the RTN and high-voltage network, exceptional outages occurred under unstable weather and in days with exceptional lighting strikes (identified based on two specific statistical methods), outages due to exceptional events, to public authorities measures and theft, as well as to external causes starting from the year 2024.

Smart monitoring enables:

- **Immediate disruption detection** and automatic reset (self-healing).
- **Dynamic load balancing** to reduce peaks and waste.
- **Demand forecasting** and resource optimisation through AI and ML.
- **Integration of renewable sources** by managing intermittence with storage and demand response.
- **Cybersecurity and data protection**, essential for connected and interoperating networks.

The application of integrated monitoring systems in power networks allowed to reduce the insurgence and the duration of local current outages from 34% to 55%[84].

A significant example is that of PPL Electrical Utilities, part of the PPL Corporation group, which provides energy to more than 1.4 million customers in Pennsylvania. The company implemented a modernisation strategy of the electrical network, along with the Fault Isolation Service Restoration (FISR) mode, part of the ADMS (Advanced Distribution Management Solution) software by GE Digital[85]. Before the ADMS adoption, disruption management was manual: operators had to identify the problem through paper maps and send teams on field to perform interventions. This required time and caused long disservices. Nowadays, owing to telemetry and to the immediate visibility of anomalies, the recovery takes place in a few minutes instead of hours, reducing the number of involved customers as well. If a line switch opens due to a fault, smart devices detect fault currents and transmit data to the ADMS software. The latter automatically elaborates a plan to isolate the damaged segment and restore power supply through alternative lines, preserving the service for the majority of users while repairs are being made. Since it started, the system avoided millions of outages and reduced blackouts by 30% compared to ten years ago. In 2021, PPL Electrical registered a 34% reduction compared to a five-year average, confirming the effectiveness of the smart technologies grid.

A significant example of application of the smart technologies grid is that of EPB Chattanooga (Tennessee, USA)[86]. The company implemented an integrated perspective fibre network with smart meters and automation devices, creating an infrastructure capable of monitoring and managing energy flow in real time. Owing to this innovation, EPB reduced current outages by 55%, showing how network digitalisation can improve service resilience and continuity. The system uses distributed sensors and automatic switches which isolate disruptions and restore power supply in a few seconds, with no human intervention. This approach not only increases reliability but enables a more efficient management of the loads and a rapid response to critical events, laying the foundation of a "self-healing" and highly performing electrical network.

Which are the advantages of adopting Smart grids and consequently smart monitoring systems?

1. Greater reliability and blackout reduction. One of the main advantages of smart grids is the ability to improve service continuity. Owing to smart devices and advanced software, the network can identify disruptions rapidly, isolate damaged areas and restore power supply in a few seconds, with no human intervention. This approach reduces both the outage number and duration, increasing system resilience also in case of extreme events[87].

2. Integration of renewable sources. Smart grids are an enabling technology for decarbonisation. They can effectively integrate renewable sources such as solar and wind power, managing their variability and ensuring network stability. This is essential to achieve the European emission reduction goals and to promote the electrification of consumption, such as transport and heating[88].

3. Energy efficiency and cost reduction. Smart grids optimise energy distribution, reducing grid losses and improving peak demand management. This turns into lower operational costs for providers and in more competitive tariffs for consumers. Moreover, owing to smart meters, users can monitor their real-time consumption and adopt more sustainable behaviours[89].

4. Active consumer participation. Smart grids transform consumer in prosumer, i.e. energy producers and consumers. Whoever has photovoltaic facilities, for example, can feed energy into the grids and participate in local markets, enhancing energy community models and collective self-consumption[90].

5. Safety and resilience. Network digitalisation enables to implement cybersecurity systems and advanced control strategies, ensuring data protection and service continuity also in presence of cyber threats. Moreover, smart grids

are designed to better resist to extreme weather events, owing to their self-repairing ability and to distributed management[91].

Water networks

The adoption of Smart Water Monitoring (SWM) systems is driven by several strategic and technological factors. First, as we have seen, increasing water shortage and global regulatory pressure make it essential to improve network efficiency and reduce losses. According to ONU and OCSE reports, water demand is due to increase significantly by 2050, with deficit risks requiring investments in advanced monitoring technologies[92].

As seen, the loss problem in Italy is extremely relevant. This is why the NRRP finances digitalisation and telecontrol interventions, facilitating the adoption of IoT sensors and predictive analysis systems to reduce losses and improve infrastructure resilience. Another essential driver is technological maturity: the availability of hydraulic, acoustic and water quality sensors connected through LoRaWAN, NB-IoT and 5G protocols (among others), together with edge and cloud platforms, enables to implement continuous monitoring at increasingly competitive costs[93]. These solutions enable to detect losses and to monitor quality parameters such as pH, turbidity and chlorine, ensuring legal compliance and consumer safety[94].

The advantages in adopting these systems are significant:

- Fewer losses, more efficiency: micro-breakages detected in real time reduce unbilled volumes and resource draw[95].
- Ongoing and resilient service: faster repairs and lower maintenance costs[96].
- Safe water: the integration of chemical and physical sensors enables to detect chemical and physical anomalies before they become emergencies[97].
- Economic efficiency: optimisation of pumping profiles and reduction of operational and energy costs[98].
- Advanced leak detection: IoT solutions for the distributed pressure and flow acquisition identify leaks with 75% accuracy, reducing intervention times from weeks to hours[99]. This is an advantage for customers also (real-time notification and automation) with a further positive impacts on the insurance front.

The benefits of adopting smart monitoring technologies

Having examined the drivers highlighted by the literature and confirmed by studies and use cases, we applied these evidences to real cases to quantify:

- economic benefits: how much can be saved by adopting the solutions illustrated above, turning innovation into a positive advantage;
- environmental benefits: emission reduction, measured in CO_2 equivalent, making smart monitoring both efficient and sustainable.

Economic benefits for civil infrastructures

Maintenance costs

According to a study by ANCE (Associazione Nazionale Costruttori Edili), the application of smart monitoring and artificial intelligence to constructions can transform the sector, offering positive benefits in terms of efficiency and cost reduction[100]. The adoption of SHM solutions and AI-based design enables to achieve:

- over 80% quality control accuracy,
- 80%-time reduction in preparing offers for tenders,
- between 20% and 30% cutting of maintenance costs, owing to predictive systems detecting anomalies before they become harmful, avoiding extraordinary interventions and machine downtime.
- Reduction of design timelines (30-50%) and delivery times (50-70%), with a direct impact on corporate competitiveness.

Road maintenance cost reduction by 20-30%

Apart from economic savings, AI enables real-time working condition monitoring, reducing risks and preventing incidents. Under the report, companies who started its adoption in 2017 have quickly recovered initial investments, with significant competitive advantages.

Impact simulation based on ANAS data

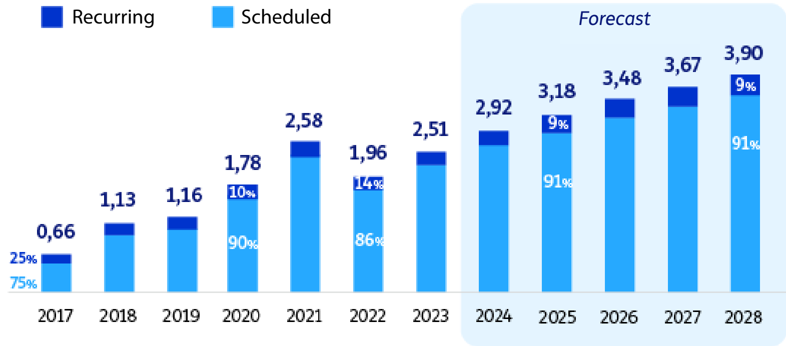
In Italy, Anas S.p.A. manages around 32,342 km of national interest road infrastructure, including trunk roads, motorways and non-toll junctions, in addition to the relevant service roads. It is the second national provider for motorways and junctions (around 1,300 km). Main activities include ordinary and extraordinary maintenance, management, safety and design, with an increasing focus on planned maintenance and modernisation.

Anas accounts show investments and maintenance-dedicated expenditure, as illustrated in the following graph.

Maintenance costs of ANAS roads

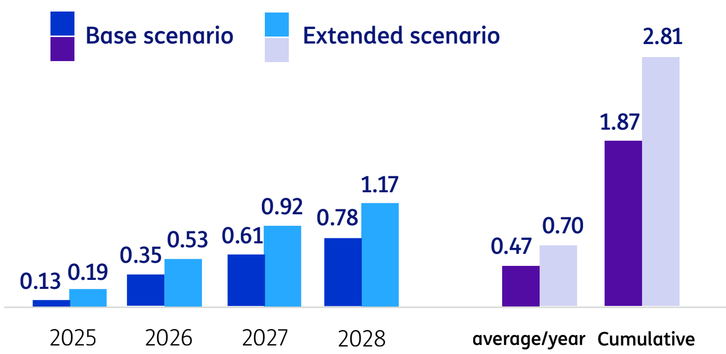
(Billion euros)

Source: ANAS 2018-2024 accounts. Elaborated by TIM Research Centre



Assuming to being able to achieve over 4 years the saving rate by rule and applying this result to a forecast on ANAS ordinary maintenance costs (both recurring and planned) in the following 4 years (2025-2028), the ***application of these technologies to the ordinary maintenance of Italian roads*** *could lead to:*

- *an* ***average/year saving*** *between* ***470 and 700 million Euros*** *(respectively in the basic 20% saving scenario and in the extended 30% saving scenario)*
- *equal to a* ***saving cumulated*** *in the period 2025-2028 between* ***1.87 and 2.81 billion Euros***



Savings on ANAS road maintenance costs driven by structural monitoring and AI

(Billion euros)

Source: 2018-2024 ANAS accounts data processed by TIM Research Centre

Collapse prevention

Between 2014 and 2020 Italy experienced a series of collapses of civil infrastructures that highlighted structural problems and maintenance deficiencies (see box).

Investigations into these events highlighted recurring factors: structural deterioration, insufficient maintenance and lack of systematic monitoring, landslides and hydrogeological instability, often worsened by extreme weather events, design errors and construction defects in some infrastructures, overloads and heavy traffic, not foreseen in the original plans. All of the above can be prevented using structural monitoring systems. Regulatory and technical measures implemented by the government immediately after the Morandi Bridge collapse aim to reduce the risk of new collapses but require ongoing investments and a culture of preventive maintenance.

Collapse prevention: we could prevent 27% of the structural collapses

A study on a steel-concrete Swiss viaduct, monitored for three years with SPM (Structural Performance Monitoring) and SHM (Structural Health Monitoring) techniques, enables to identify a precise measure: the monitoring increases structural compliance by 36% and can prevent up to 27% of the collapses[101-102_103]. Assuming a uniform compliance level distribution between 0 and 1 in case of collapse (a prudent assumption, since it is highly probable that in many cases compliance is just below 1), we find that an ongoing structural monitoring can prevent 27%[104] of infrastructural collapses.

Bridge collapses in Italy

- 2014: collapse of the Petrulla viaduct (SS 626, Licata), four wounded and reconstruction completed in 2018.
- 2015: landslide on the Himera viaduct (A19 Palermo-Catania), prolonged closure of a strategic artery.
- 2016: collapse of an overpass on the Milano-Lecco, a casualty and four wounded.
- 2017: collapse of the Fossano viaduct (with no casualties) and collapse of a bridge on the A14 in Ancona during works (two casualties).
- 2018: the Morandi Bridge disaster in Genoa, 43 casualties and devastating impact on economy and mobility.
- 2019: landslide on the A6 Torino-Savona, prolonged closure.
- 2020: collapse of the Albiano Magra bridge, a wounded.

Through a structural monitoring it is possible to **prevent any collapse caused by:**

- **Progressive and invisible deterioration** (steel corrosion, precompression cables, metal fatigue).
- **Sudden and unpredictable events** (seisms, floods, naval vessel collisions).
- **Design or construction errors** showing over time.

Which are the structural monitoring costs and the economic advantages of its application? Its value emerges analysing different levels of prevention:

Severe collapses: smart monitoring systems are designed to detect critical problems – such as cable corrosion, foundation subsidence or metal joint fatigue – long before they can cause real damage, reducing the risk of sudden collapses to almost zero.

Intermediate collapses: significant damage (deep cracking or anomalous strains) detection enables to intervene before a minor damage becomes harmful. It reduces maintenance costs and preserves the useful life of the structure.

Minor damages: prevention of microcracking and wear development, reducing maintenance costs.

Structural monitoring is efficient only if applied strategically. Four factors make a difference:

Coverage and quality of the system: monitoring only large bridges or public buildings and minor viaducts makes a big difference.

Infrastructure age and state: in Countries with dated works, such as Italy and the USA, prevention potential is enormous.

Environmental conditions and extreme events: after seisms, floods or landslides, sensor data are crucial to assess safety.

Management responsiveness: monitoring is useless if alerts are not analysed and turned into positive actions.

Collected studies highlight the economic advantages deriving from structural monitoring application:

Maintenance costs reduction: monitoring-based predictive maintenance can reduce costs by 25-40% compared to planned maintenance and up to 70% compared to reactive maintenance[105].

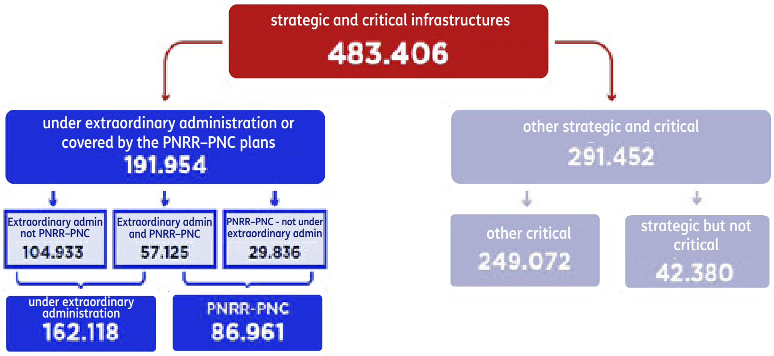
Useful life extension: SHM systems may extend a structure life by decades, avoiding costly reconstructions.

Cost-benefit ratio: monitoring system costs are negligible compared to the economic losses caused by closures or collapses.

Impact simulation: savings by the adoption of SHM systems

Here are some examples.

- ***San Giorgio Bridge**, restored after the Morandi bridge collapse. Cost of around €202 million. The new bridge is equipped with an extremely extensive monitoring in order to avoid any potential future tragedy[106].*
- ***Scafa Bridge** (Fiumicino). Closed in 2018 for serious structural problems and risk of collapse, with heavy repercussions on the mobility between Ostia and Fiumicino. The reconstruction is under the strategic works for the Jubilee 2025[107]. The construction of the new bridge should last about three years, with an estimated cost of around 110 million Euros[108].*
- ***Cannavino Viaduct** (Celico, Calabria) structural challenges[109], repeated closures, safety works and a demolition/reconstruction project, with NRRP funds amounting to 17.2 million Euros[110-111-112].*



Here are the critical infrastructure investments expected in the following years. Under the 2024 Chamber of Deputies Annual Report on strategic and priority infrastructures the cost of the priority strategic infrastructure on 31 August 2024 was equal to 483 billion Euros, for which the financial availability amounted to 343 billion, equal to 71% of the cost. Infrastructures under receivership or the NRRP-PNC programmes[113] had a cost of 192 billion Euros (40% of the total strategic and priority infrastructure) and a 71% financial coverage.

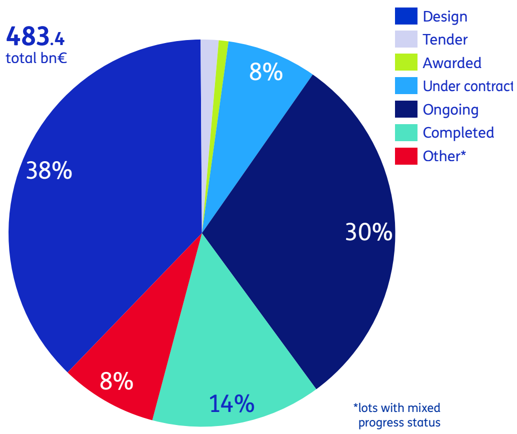
Other national strategic and priority infrastructure, not provided by NRRP nor under receivership but critical to reduce the Country's infrastructural gap, at the time of the survey had a cost of 291 billion with 71% financial coverage.

Most of the resources, equal to 79% of the programme, aim to potentiate railway and road networks: around 205.6 billion for railway (42.5%) and 161.8 billion for road networks (33.5%). Further 13.5 billion are for the Strait of Messina Bridge, while the remaining 17.5% – around 86 billion – is for urban systems, ports, airports and cycle routes. A 3.5% residual share finances Mo.S.E., other infrastructural interventions and public construction.

By 31 August 2024, works worth around 69 billion Euros had already been completed, while those worth 146 billion were underway, with the remaining infrastructures in different development stages.

Considering that the NRRP-PNC funds must be spent by 2026 and that FSC fundings are planned up to 2027 but usable by 2030, we can expect a cost distribution up to 2030 based on current progress and on Structural Budget Plan forecasts[114].

Costs of infrastructure works by progress status (bn€- %)



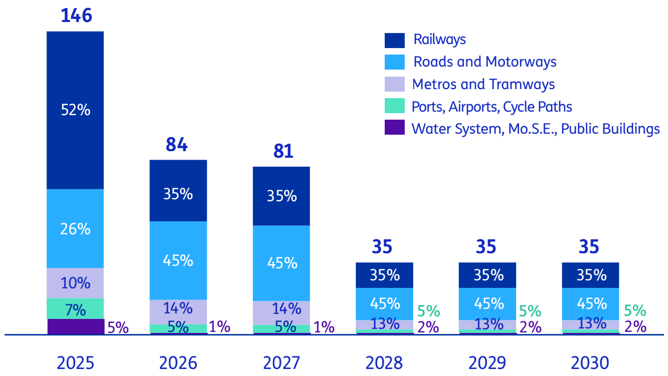
Source: Camera dei Deputati - Infrastrutture strategiche e prioritarie 2024

To estimate the total investments provided in 2026 and 2027, we used Public Administration data on gross fixed investment in the 2016-2027 decade, as indicated in the mid-term Structural Budget Plan forecasts. On these forecasts, an investment breakdown by typology has been applied, in compliance with the plan. The remains, valid for the three-year period 2028-2030, was divided equally over the three years plan to minimise errors.

As to large investments, we followed the hypotheses formulated by D. Inaudi in Cost-Benefits Analysis in SHM Projects[115], that you can find below.

Supposing to instal SHM systems on bridges due to be replaced, based on the estimated structural conditions[116], the cost of SHM system and engineering data analysis is typically around 3% of reconstruction costs[117]. This analysis helps determine whether the bridge needs to be replaced, rehabilitated or can continue functioning without intervention.

Planned investments in critical infrastructure (bn€)



Based on D. Inaudi- Cost-Benefits Analysis in SHM Projects[118], we assume that:

- *20% of bridges are in better conditions than expected and do not require any intervention.*
- *20% of the bridges can be rehabilitated with 30% of the replacement cost.*
- *60% of the bridges actually need to be replaced.*

Still following the analysis, supposing that, without a preliminary assessment, the replacement cost for each bridge be equal to 100%, we can estimate the structural monitoring (SHM) strategy cost as follows:

- *Equipment and data analysis cost: 3%*
- *Replacement of the unsavable bridges: 60% (100% of the cost for 60% of the bridges)*
- *Repair of rehabilitated bridges: 6% (30% of the cost for 20% of the bridges)*
- *Bridges not requiring intervention: 0% (20% of the bridges)*

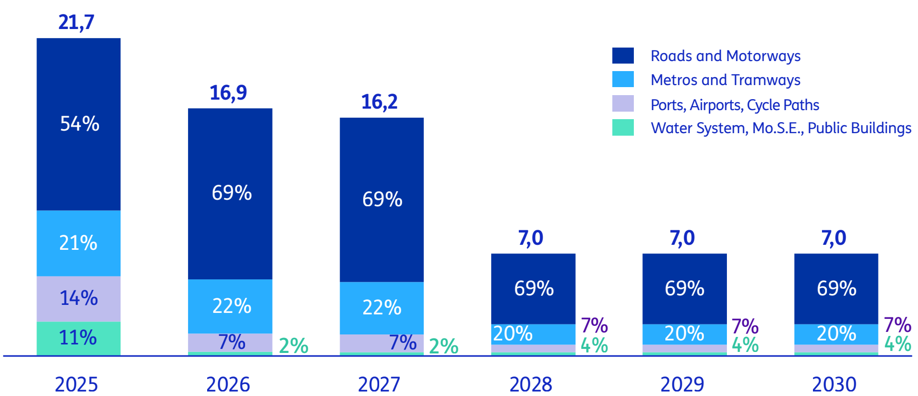
Total cost with SHM: 69% compared to 100% of the established cost.

Estimated savings: 31%.

This example, based on realistic and conservative data, shows that the systemic implementation of SHM system on all bridges due to be replaced can lead to a total investment reduction by 31% for the owner. This result is obtained by postponing in a safe way 40% of the replacements. This positive advantage is attractive for the owners, as it enables immediate savings[119].

Therefore, extending this hypothesis also to new civil constructions, as a basis for calculation we can use data planned for critical infrastructure in subsequent years. In a conservative way we considered the works foreseen in the plan with the exclusion of railways, whose monitoring is not examined in depth in this study.

Applying 31% savings on costs expected from 2026 to 2030, we obtain annual savings of more than 16 billion Euros in the first two years, and of 7 billion Euros per year in the last three, for a cumulative total of more than 54 billion Euros in the five-year period.



Planned investments in critical infrastructure (bn€)

In conclusion, apart from the qualitative reasons leading to the adoption of SHM systems described in the previous chapter, here are the main positive benefits of structural monitoring:

1. Extended useful life: efficient monitoring can extend the life of a structure by 20-30%, delaying very expensive reconstructions.
2. Maintenance Cost Reduction: addressing a minor problem costs 10-100 times less than repairing a major damage or reconstructing. 25-40% savings on infrastructure life cycle costs are estimated.
3. Limited Social and Economic Impact: avoiding sudden closures of an essential viaduct (such as a motorway) prevents heavy economic losses for the Country system (logistic block, diversions, delays).

Economic benefits for power networks

When an electrical network is smart?

A full upgrade is needed, including:

- Second generation smart meters.
- Advanced sensors for real-time monitoring.
- Distributed automation on medium and low voltage.
- ADMS systems for dynamic and predictive management.
- Storage and renewables integration for network balance.
- Demand response platforms to modulate consumption.

Assess the benefits deriving from smart grid large-scale implementation in Italy is a complex exercise, as it depends on interconnected variables: the already achieved level of digitalisation, electrical grid configuration, incentive politics and the level of penetration of renewable sources.

However, based on international studies and the Italian electrical system features, it is possible to provide both a quantitative and qualitative estimate of the expected benefits.

Our Country has an advantage position compared to EU average, owing to the digitalisation started with smart meters.

Therefore, the expected benefits are incremental, not "from scratch", but still significant.

We can identify 4 areas of improvement

1 Reduction of technical losses

Technical losses indicate dispersed energy along lines and transformers due to electrical resistance. Smart grids enable to reduce losses owing to:

- Real-time monitoring to identify anomalies and intervene immediately.
- Dynamic network reconfiguration to balance loads.

- Optimal tension control to minimise Joule losses.

In 2024, in Italy, gross domestic energy consumption was equal to 321.6 TWh. Terna annual report shows technical losses year by year, typically between 5 and 6% in the relevant timeline[120].

In 2024 technical losses were equal to 6.3% of energy consumption[121].

Under the Joint Research Centre, smart grids are essential for the digitalisation of the European electrical system and for achieving the Green Deal objectives of decarbonisation and integration of renewable sources. They both improve efficiency and create a digital ecosystem connecting smart households, energy communities and electrical mobility. **Among their positive benefits there is the reduction of network losses estimated between 1% and 3% per year**[122].

For a prudent estimate, we consider an additional 1% reduction determined by a massive introduction of smart grids. Based on 2024 data, losses would go from 6.5% to 5.5% per year, with a reduction of 3.13 TWh/year. Under the 2024 Italian wholesale exchange average single national price (PUN) of 108.5€ per MWh, **there would be savings of around 339 million Euros per year.**

2 Peak Load Transfer benefits

Smart grids enable programmes of Demand Response (DR) and dynamic tariffs, leading consumers to shift consumption from peak hours to less congested time slots. This reduces network pressure and generation costs.

In Italy, the **national peak load reached 57.5 GW in 2024**[123]. According to studies and pilot projects carried out by **RSE** and **Terna**, a Demand Response aggressive programme could reduce peak loads by 5-10%[124]. Using a 5% conservative estimate and considering a peak average value of 57.8 GW (average over the last ten years, excluded 2020), the benefit of non-generated energy is 2.9 GW.

This value reflects both the energy saved and the capacity made available, directly affecting the Capacity Market. This market, introduced to ensure the safety of electrical systems, rewards power availability with values ranging between 33 and 78 €/kW/year, according to tender results[125]. Using last years' value, and specifically the 2027 value of 47 €/kW/year, the estimated economic benefit (i.e. capacity value) amounts to approx. 136 million Euros per year[126].

This advantage is combined with the savings on energy not produced by peak plants, which are characterised by very high generation costs – over 200 €/MWh. Assuming an average operation of 200 hours/year for these plants, and energy saving of 2.9 GW/year, and valuing this energy at the difference between peak cost (200 €/MWh) and wholesale PUN (108.5 €/MWh), the resulting additional benefit amounts to about 53 million Euros per year in avoided production costs. Overall, the combination of reduced capacity cost and peak generation costs results in an economic impact of more than 188 million Euros per year, not to mention the environmental benefits associated with reduced production from thermoelectrical sources.

At the Country system level then, the overall estimated benefits amount to about 530 million Euros/year in technical loss reduction and peak energy demand management.

3 Energy saving benefits

Smart grids generate economic advantages for households through two main mechanisms:

1. **Greater energy efficiency**: smart meters enable real-time consumption monitoring, waste reduction and more virtuous behaviours.

2. **Consumption reduction in peak hours:** owing to dynamic tariffs, customers shift consumption (ex. washing machines, dishwashers, electrical vehicle charging) from peak hours to less costly time slots. This lowers the bill and generates lower peak hour loads, reducing the pressure on peak power plants, which are the costliest and most polluting.

Estimates on the efficiency induced by smart meters alone are relatively low: 0.5-1.5% of a household's total consumption[127]. Considering that domestic consumption accounts for about 22.5% of the national total[128], equal to 66 TWh/year in 2024, we can expect a 1% saving on domestic consumption, i.e. 6.59 MWh/year for Italy based on 2024 data.

Using the 2024 retail average price per household, equal to 217 €/MWh[129], the overall economic benefit for the country is over 143M€/year.

This saving, although apparently modest in percentual terms, has a significant impact:

- **reducing households' energy expenditure**,
- **contributing to sustainability**, as each kWh saved reduces CO_2 emissions,
- **supporting the stability of the system**, reducing demand in critical hours.

4 Other Non-Quantified (yet crucial) Benefits

- **Integration of Renewable Sources**: smart systems play an essential role in the integration of strongly variable renewable sources such as solar and wind power. In this way, it is possible to ensure stability and service continuity to achieve the objectives established by the PNIEC (Piano Nazionale Integrato per l'Energia e il Clima).

- **Reliability and Quality of Service (SAIDI/SAIFI)**: network automation and self-reconfiguration reduce the length and extension of the disruption allowing to rapidly isolate damaged sections and restore the service in much shorter times compared to traditional systems. This improves quality indicators (SAIDI and SAIFI) and prevents huge economic damage (damages from prolonged outages can amount to tens of million Euros per year).

- **Safety and Resilience**: a smarter network is also a safer network. The ability to monitor and address critical situations (cyberattacks, extreme climate events) in real time represents a strategic advantage for service continuity and the protection of the infrastructure.

- **New Services and Markets:** network technological evolution favours active participation of citizens and energy communities. Some examples are the prosumer market (consumers producing energy), energy communities and the smart charging of electrical vehicles.

Reducing the cost of water networks

In Italy, the management of water resources represents a strategic issue, mainly regulated by part three of the Environmental Code (D.L. 152/2006), which implemented the European Framework Directive 2000/60/EC and introduced the principle of the integrated use of water resources. This norm signed the passage from a fragmented to an Integrated Water Service (SII) management, organised in Optimal Territorial Areas (OTA), with the aim to ensure service efficiency, cost-effectiveness and sustainability.

Notwithstanding the regulatory progress and ARERA supervision, the Italian water sector still has structural and management challenges. The main issues are:

- High water losses: according to data by ARERA, in 2023 loss percentage reached 41.8% at the national level, with peaks higher than 55% in the South, against a 25% European average. This is worsened by network obsolesce, 60% of which has more than 30 years of life. Moreover, 25% of the latter exceeded 70 years of life, while in several Italian historical centres there are still pipes dating back to the post-unification period[130].

- Lack of investments: albeit in recent years there has been an increase, with a pro capite average of 70 Euros in 2023 (+113% compared to the previous decade), the economy management remain at only 11 Euros pro capite, very far from European standards (82 Euros). This gap is particularly evident in the South and in the Islands, where most of the fragmented management is concentrated[131].

- Fragmented management: despite the legislation aim at management uniqueness per OTA, there are still more than 1,300 municipalities with economy management, equal to 12% of the population, 95% of which located in the South[132]. This fragmentation hinders economies of scale and the ability to invest.

- High consumption and water withdrawal: Italy confirms its first place in Europe per absolute volumes of water withdrawn for potable use (9.14 billion m^3 in 2022), equal to 424 litres per inhabitant per day, against a European average of 45-90 litres[133]. The pressure on the resource, together with the growing frequency of drought events, increases the risk of water stress.

To address these challenges, in recent years significative interventions have been activated, among which NRRP measures (Mission 2, Component 4), allocating 4.5 billion Euros to the water sector, and the Piano Nazionale di Interventi Infrastrutturali e per la Sicurezza nel settore idrico (PNIISSI), with an estimated requirement of 12 billion Euros per 418 new interventions. However, as pointed out by the Court of Audit and by ARERA, achieving these objectives requires strengthening governance and an acceleration in implementing projects, especially in the southern areas, to reduce the so-called water service divide[134].

Water Monitoring role in water management

Water monitoring constitutes a strategic element for the efficiency of the Integrated Water Service (SII), as provided by the Environmental Code (D.L. 152/2006) and by Directive 2000/60/EC, establishing the principle of sustainable and integrated use of water resources. This activity is consistent with the technical quality objectives established by ARERA (Decision 917/2017/R/IDR), including specific loss reduction indicators and better service continuity.

Here we tried to quantify some of the main advantages related to the adoption of smart water network monitoring.

Reduction of water losses

Real-time water network monitoring enables to identify anomalies and leaks, reducing waste and maintenance costs. Studies indicate an overall reduction in losses up to 4%, when the network is districted for timely interventions[135].

On-field analysis shows that smart meter adoption by customers enables a drastic post-meter reduction of water losses, owing to the ability of these devices to provide high resolution data on domestic consumption. Unlike traditional meters, smart systems record and transmit water volumes at very short intervals (from 1 to 10 seconds), allowing to identify anomalous patterns such as ongoing flows throughout the night, typical of internal losses[136].

A study performed in Australia showed that, through smart meter implementation and targeted information sent to users, it has been possible to reduce the Minimum Night Flow (MNF) – key indicator to detect losses – by about 89%, value that corresponds to the almost total elimination of domestic losses. This result was achieved owing to two factors:

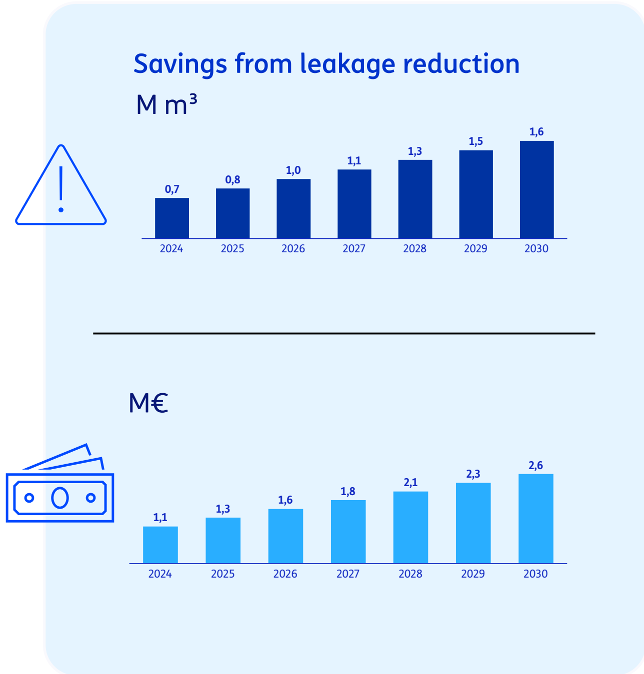
- Rapid loss detection: granular data enable to distinguish between normal consumption and anomalous flows, even those with small intensity (ex. drippings taps or faulty drains).
- Immediate user intervention: targeted communication and monitoring-generated awareness lead customers to repair losses quickly.

According to authors, the combination of technology and proactive behaviours is the key to achieving high reductions, with both economic and environmental benefits. Moreover, the paper points out that post-meter losses can account for up to 10% of total residential consumption; therefore, their containment has a significant impact on global water demand[137].

CENTRO STUDI TIM

A study pointed out that leak detection goes from an average of 90 days in traditional networks to about 7 days[138] in networks equipped with smart meters and sensors. In 2023 in Italy there were 21 million meters, 17% of which were smart meters (3.5 million)[139]. The NRRP allocated around 900 million Euros to be invested in water distribution network loss reduction projects and in digitalisation and infrastructure monitoring interventions[140]. From August 2022 to September 2023, 29 tenders to award a total 2.7 million water meters had taken place, for a contract total value of about 250 million Euros[141], excluded installation and ancillary services.

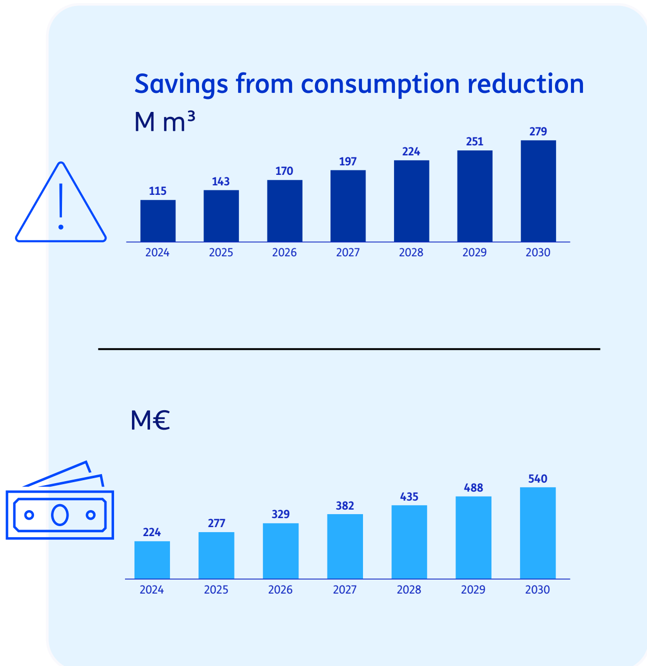
Thus, we developed a replacement hypothesis of 1 million meters per year, considering only user meters and excluding the ones installed on network pipes. This hypothesis is consistent with tender provisions, and this replacement scale was in fact achieved by water system operators in the United Kingdom[142]. Considering an average tariff per mc of water equal to 1.16€[143] (only water raw material), this would allow a saving of 2.6 billion€ in 2030 in Italy, for about 10.4 billion Euros cumulated in the years 2026-2030.



Consumption optimisation and demand management

Consumption data analysis enables saving policies and tariffs based on real consumption, in line with the full cost recovery principle (art. 154 Environmental Code). On-field, a greater transparency on consumption has generated between 10 and 18% reduction in water demand[144].

Taking an on-field case from the United Kingdom as a reference[145] and maintaining the prior progression of 1 million meters per year[146], consumption reduction per user combined with a higher number of smart meters, also considering the cost of

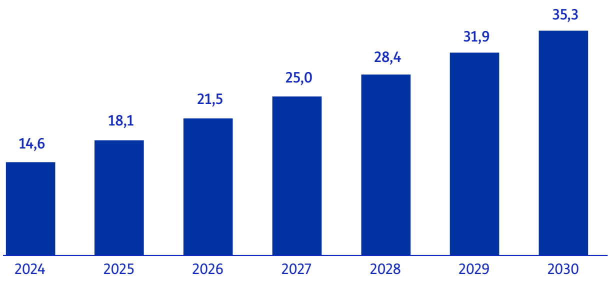


water, this time complete[147], equal to 1.95€/mc on average, by 2030 results in a cumulated saving of nearly 1.4 billion of mc of water for a value of about 2.7 billion€.

Reading cost reduction

Smart meter adoption transforms water service management, drastically reducing operational costs related to consumption reading. In traditional systems, operators read about 300 meters in 8 hours; with smart meters, the same resource can manage up to 20,000 devices owing to automatic data transmission and remote reading[148] with cost savings. According to Sensus projects carried out by U.S. operators, the cost per single reading decreases by 0.80 € compared to mechanical systems[149]. Assuming an average of 4 annual readings for user with a consumption of 3,000 m³/year or less – which represents about 95% of the total – and 6 annual readings for higher-consumption users[150], the estimated cumulative saving could reach about 175 million Euros by 2030. Beyond the economic benefit, digitalisation eliminates manual errors, accelerates data availability and supports more efficient and sustainable management policies, freeing up resources which can be invested in infrastructures and innovation.

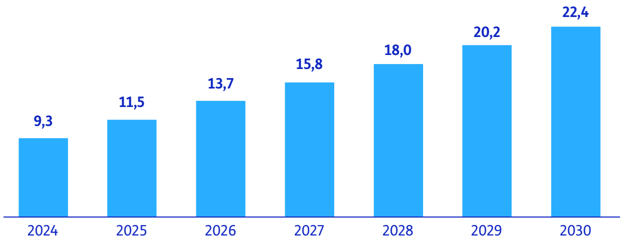
Savings from improved smart-meter readability (M€)



Reduction of loss repairing

Responding promptly to leaks reduces both times and costs, preventing more significant damage. At present, repairs activities account for about 16% of water service operational costs (95 € per inhabitant/year)[151]. Moreover, network traditional management, based on reactive interventions, requires mobilising teams, incurring labour and material costs, and causing inconvenience to users.

Savings from reduced leakage-repair costs (M€)



Instead, smart technologies and smart meters rely on a predictive approach that enables immediate detection of anomalies, automatic reporting and targeted interventions. Estimated savings are up to 5% of this component. In economic terms, the benefits are significant: considering the weight of repair activities on total Opex, by 2030 cumulated savings could reach tens of million Euros, freeing resources for infrastructural investments and innovation[152]. In Italy, 93.2% of the population is served by water services. Considering the number of inhabitants involved in the progressive replacement of traditional devices with smart meters, and the resulting reduction in repair costs, cumulative savings could exceed 110 M€ by 2030.

Loss reduction generates a double advantage: lower direct repair costs and less waste of treated water, pumping energy and potability chemicals, with a positive impact on environmental sustainability.

CHAPTER 8: Benefits for the environment

Smart civil infrastructures: greener bridges and roads

The smart monitoring of civil infrastructures contributes to decarbonisation in several ways, owing to digital technologies such as IoT sensors, artificial intelligence and big data analysis.

Ongoing monitoring enables to promptly identify structural problems, facilitating preventive interventions and reducing the need of urgent works with high environmental impact.

Under the AIS Position Paper, digitalisation can reduce CO_2 emissions by up to 30% during the infrastructure life cycle, owing to proactive management and waste reduction[153]: sensors and analysis platforms monitor vibrations, loads and energy. These data, processed with AI algorithms, enable to optimise energy and material use, reducing emissions and overall consumption. The use of wireless sensors in critical and existing infrastructure improves management and favours decarbonisation.

Impact simulation

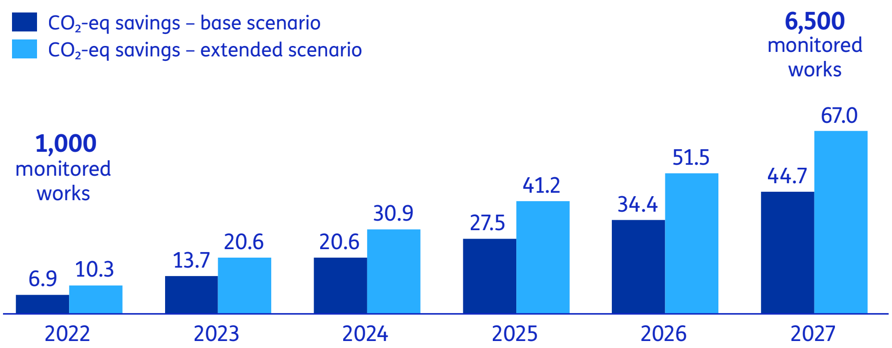
To assess the environmental impact of smart maintenance, the supervision needs of critical infrastructure currently lacking monitoring have been considered.

In 2022 ANAS adopted the SHM monitoring (Structural Health Monitoring) model, supported by 275 million Euros of the NRRP Complementary Fund, for the dynamic monitoring and remote control of 1,000 bridges and viaducts by 2026[154]. With the new NRRP investments of 100 M/year in 2023, 2024, 2025 and 75 M in 2026, the system is expected to be extended to more than 12,000 structures, including a further 5,500 critical works equipped with remote monitoring sensors[155].

In 2023, traditional supervision involved 30,708 visual inspections, requiring ANAS inspectors to cover a total of 1,944,750 Km (i.e. 50-100 km per inspection, including travel between works and access points). The growing focus on an increasingly aging infrastructural asset led to 47,956 inspections in 2024. This increase resulted from the higher inspection frequency required for works with High and Medium/High CdA, which shifted from once a *year to every six months, representing a 55% rise compared to the previous year[156]. Although the ANAS fleet is being renewed, with combustion-engine cars replaced by electrical cars, the environmental impact of inspection-related travel across the country remains high, due to the energy footprint of electricity production.*

Applying the reduction in visual inspections enabled by monitoring systems – 20% in the basic scenario and 30% in the extended scenario – to the annual kms inspected, and calculating the resulting savings assuming 1,000 works monitored per year (1,500 in 2027), results in a total of 6,500 critical works monitored by the end of 2027, in line with MIT provisions. Using the ISPRA reference value of 135.6 g of CO_2eq/km for Hybrid petrol passenger vehicles[157] (a conservative assumption not knowing the composition of the car fleet between passenger and light commercial vehicles, which are largely equipped with diesel engines and have a much higher polluting impact in terms of g CO_2eq/km emitted), the reduction in annual kms travelled enabled by the introduction of new technologies would allow a cut in emissions between 9 and 14 ktCO_2eq per year for the first 1,000 monitored works alone. Once fully operational, with 6,500 works monitored in 2027, the annual reduction in CO_2 equivalent emissions would rise to between 45 and 67 ktCO_2eq per year[158].

Estimated GHG savings from reduced travel for ANAS network inspections (ktCO_2eq)



Using tools such as Building Information Modelling (BIM) and digital twins in infrastructure design allows to simulate different scenarios and assess the environmental impact of design choices, optimising the life cycle of the work. This approach reduces the overall carbon footprint by integrating data on materials, processes and energy consumption.

Climate impact of power monitoring

In electrical infrastructures, smart monitoring is a strategic lever accelerating transition towards low-emission infrastructure, since it reduces waste, optimises resources, enables renewables integration and favours predictive maintenance. In other words, digitalising makes more resilient infrastructures and accelerates the path towards decarbonisation, in line with the goals of the European Green Deal and its 2050 roadmap[159].

Legacy networks, designed for centralised energy flows, are no longer adequate in a context dominated by intermittent renewable sources, consumption electrification and prosumer growth. This new scenario requires dynamic and adaptive smart grids capable of responding in real time to energy demand and offer, thereby improving resilience and efficiency. Moreover, sensor and IoT system integration enables continuous data collection on lines, loads and environmental conditions, reducing the risk of disruptions and optimising maintenance. This in turn lowers the need for emergency interventions, which typically generate higher emissions. In short, the combined use of AI and IoT in smart grids, not only enables an optimised, safe and efficient management, but also contributes to reducing CO_2 emissions. Predictive data analysis anticipates consumption peaks and enhances the use of renewable sources, thus limiting the use of fossil resources[160].

Impact simulation

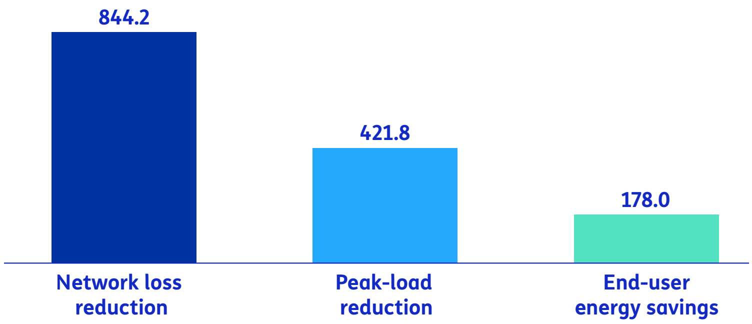
The climate impact of smart monitoring depends on the emission factor of the Italian electricity mix, which indicates how much CO_2eq is produced per kWh. This value varies over time and changes according to the energy sources used (renewables, gas, coal). According to Terna and ISPRA, the average carbon intensity of the Italian electricity mix has declined steadily since 2015, decreasing from 406 gCO_2/kWh in 2015 to 270g CO_2eq/kWh in 2024[161], mainly due to renewable sources. For the purpose of our estimates we assume an emission factor of 270 g CO_2eq/kWh.

Based on the energy savings previously estimated for economic benefits, we assess the CO_2eq reduction:

- *Network loss reduction: 3.13 TWh/year saved, which, when multiplied by the emission factor of the Italian electricity mix, results in a reduction of 844.1K t of CO_2eq/year.*
- *Peak load reduction: peaks are typically met by fuel oil or coal plants, which have a much higher carbon intensity than the average mix. According to the EPA[162] oil fuel units and gas turbines emit approx. 730 g*

CO_2eq/kWh. Therefore, avoiding 577,778 MWh of peak energy corresponds to around 422K t of CO_2eq/year.

- *Final customers' energy savings: 0.66 TWh/year, which, when multiplied with the emission factor of the Italian electricity mix, corresponds to a reduction of 178K t CO_2eq/year.*



Estimated GHG savings from electricity-grid actions
(ktCO2eq/year)

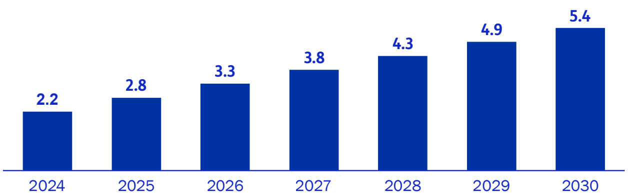
Environmental benefits of smart metering and water network monitoring

For water infrastructures, we apply the same approach starting from the scheme used to assess economic impacts.

In the United Kingdom, different use cases show that smart meters installed at final users' premises reduce CO_2eq emissions by 0.5%. According to estimates, each household generates 2.67 kgCO_2eq per day, for an average water consumption of 138 litres[163]. Scaling this estimate to the Italian scope, where the pro capite billed daily water consumption rests at 215 litres per day (source: ISTAT)[164], we estimate that each household produces 4.16 kgCO2eq daily.

Therefore, the installation of 1 million water monitoring smart meters per year could generate a significant impact: calculated consumption savings lead to a reduction of 2.23 MtCO_2eq in 2024, up to 5.39 MtCO_2eq in 2030. In ISPRA forecasts, this accounts for 0.6% of total greenhouse gas emissions in Italy in 2024[165] (excluded LULUCF)[166], with a weight in the following years growing up to 1.58% in 2030, despite the expected emission degrowth.

Greenhouse-gas emission reduction (MtCO_2eq)



Beyond reduced consumption, additional benefits come from operational and environmental improvements, such as:

- Reduction of water losses, with less energy consumption for pumping and treatment.
- Pressure optimisation, reducing energy waste and increasing system efficiency.
- Early detection of contaminants, avoiding high energy intensity emergency purification processes.

Added to these are further energy savings linked to strategic plants efficiency:

- Water makers, with an expected reduction of about 1 GWh per day.
- Sewage sludge treatment and purification plants, with potential consumption reduction up to 30%[167].

Reduction in bottled water consumption

Sensors used for water smart monitoring also provide continuous control of the quality of water in the waterworks. Adopting smart monitoring can help increase public confidence in tap water, which is currently low: according to a survey conducted by Ambrosetti[168], only 1 in 3 Italians trust the water supplied by waterworks. This is why Italy is the first European consumer of bottled water (249 l/ab/year, of which 72% natural water[169]), with enormous environmental impacts: 10 billion litres in PET, 7 billion of non-recycled bottles[170], 850 kt CO_2eq/year.

Impact simulation

ARERA uses the total hours of water-supply interruption as a key indicator for assessing the efficiency of the SII (Sistema Idrico Integrato) and water networks. This indicator (M2) has low values (less than 20 hours) in almost all regions and a national average of 59 hours[171] in 2023. However, given the very high variability of the M2 indicator, a more meaningful measure of water-service efficiency may be the percentage of households who complain about irregularity in water supply. According to ISTAT (2024), these percentages are highest in the South (14.7%) and in the Islands (up to 26.3%), compared with the national average of 8.7%. It should be noted that the share of households who do not trust drinking tap water, as measured by ISTAT, is strongly correlated (70%) with the share of households complaining about irregularities in water supply[172].

So, users' trust in water networks is based on complex factors, which can yet be managed through smart monitoring.

Even without calculating impacts of transporting mineral water bottles on greenhouse gas emissions, as many as 10 billion litres consumed every year are contained in PETs[173].

Considering that:

- *7 billion disposable PET bottles are not recycled;*
- *PET recycling waist is equal to 32% of the initial product, and only 5% is destined to the production of new bottles,*

every year 850k CO2eq tons are used to make 278k tons of non-recycled PET.

With the adoption of smart meters and the timely release of information on the quality of the water supplied to households, the use of bottled water could decrease. Today, concerns about tap-water quality affect 27.9% of Italians who consume mineral water[174] and 28.8% of Italian households who do not trust drinking tap water[175].

Conclusions

Another important benefit of infrastructural monitoring relates to its impact on Gross Domestic Product. Much has been written about the multiplier effect of infrastructure investments, both in terms of GDP and jobs. According to an analysis conducted in 2018 by Oxera for ICE (Agency for the promotion abroad and internationalisation of Italian companies)[176]the infrastructure multiplier stays between 1.5 and 2.7 investment value, depending on the type of investment.

A similar analysis was carried out by WIOD/McKinsey Global Institute[177], which estimates a short-term GDP multiplier of 0.81 for constructions and a job-creation multiplier of 11.95 for every dollar invested. Banca d'Italia reports comparable results[178] and indicates that the GDP multiplier increases to 1.5 in the medium term (2-5 years).

From this perspective, since infrastructural monitoring generates economic savings and reduces infrastructure management costs once applied, we can say that its effect on the country system is to lessen the impact of infrastructure investments on GDP.

If the freed resources were invested in maintenance rather than new works, the economic impact on GDP would be very similar, since the maintenance multiplier is comparable to that of infrastructure investments.

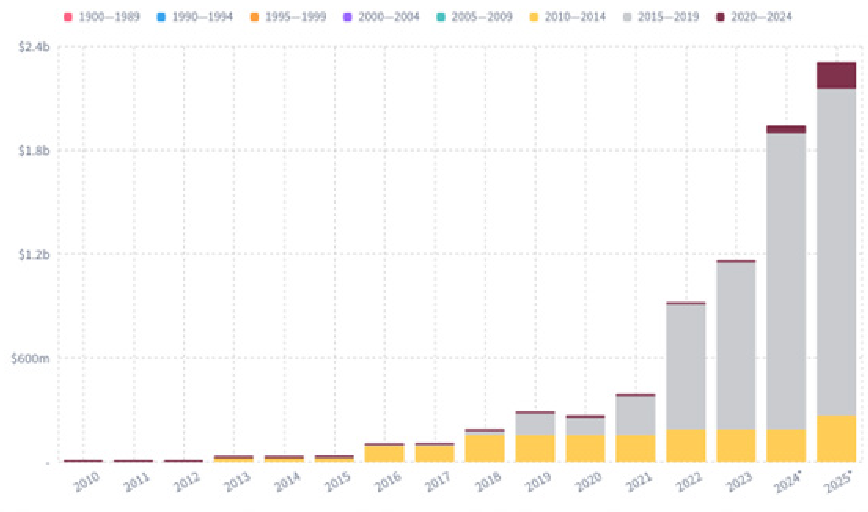
However, maintenance investments, which typically aim to compensate natural infrastructure deterioration, can also become a powerful countercyclical tool, since they concern smaller, brief and less complex projects, whose shorter implementation times allow a rapid activation of private production factors, job included[179]. The implementation pace is also linked to shorter authorisation procedures than for new works, that to be built can hinder the usability of existing works and generate negative externalities.

As to smart maintenance, we have seen how it brings medium and long-term advantages on the state of infrastructures, on their functionalities, on safety and on the environmental impact. Moreover, the impact of savings which can be achieved at a systemic level is such that it does not end with smart monitoring investments, but produces effects in the medium and long term, thus inducing a virtuous circle which, in turn, brings positive effects both for the country's economy, its infrastructural assets and the environment.

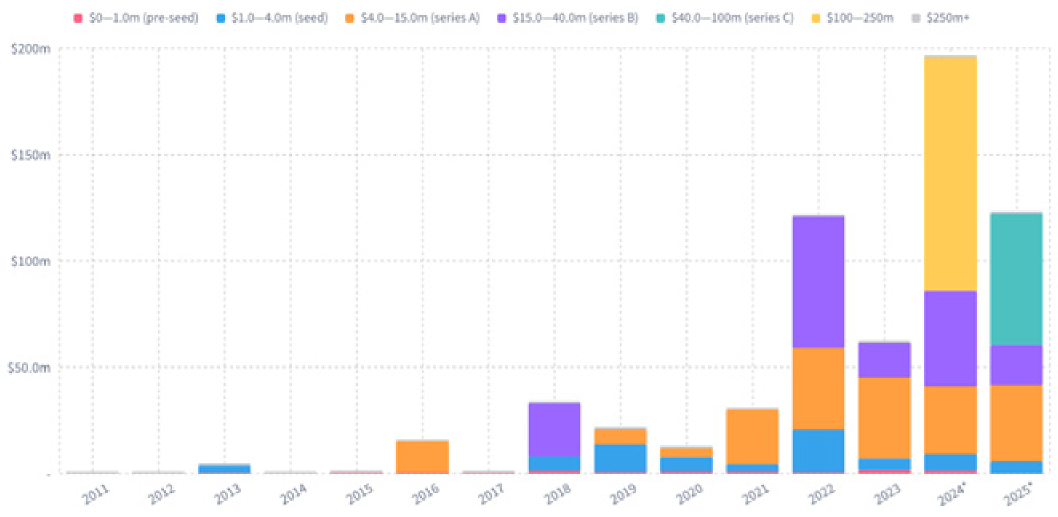
TIM Smart Infrastructure Challenge

The TIM Smart Infrastructure Challenge initiative has attracted considerable interest, with 106 applicants, of which 70 Italian and 36 international companies. The proposals are mainly concentrated on two areas: the monitoring of complex and water infrastructure (74 applicants) and Building and Energy Management (BEMS) systems (32 applicants). At the European level, there has been a significant participation, with realities from the United Kingdom, Germany, Spain, France and Belgium, as well as from the United States, Brazil and Ukraine.

The focus on Italian and European startups in the smart infrastructure sector, according to Dealroom data[180], highlights a rapidly growing ecosystem: more than 60 companies with an overall value of 2.3 billion dollars, mainly established between 2015 and 2019.



The financing trend saw an acceleration starting from 2022, as shown in the following graph.



In 2025 alone, up to the end of August, more than 122 million dollars have already been raised through ten round of investment. Here are the 10 companies who have received the most funding.

Name	Investors	Market	Location	Round Valuation	Latest Round	Date
Aerones	Change Ventures S2G Ventures Activate Capital Lightrock Blume Equityt	B2B Energy robotics clean energy	Riga, Latvia	$248m - $372m	$62.0m LATE VC	Jun 2025
Optics11	SET Ventures Join Capital FORWARD.one Venture Capital	B2B semiconductors engineering and manufacturing equipment	Amsterdam, Netherlands	€68.0m-€102m	€17.0m EARLY VC	May 2025
Voliro	Cherry Ventures noa	B2B robotics	Zurich, Switzerland	$44.0m-$66.0m	$11.0m SERIES A	Jun 2025
CSignum	Scottish Enterprise Growth Investments Par Equity Archangels Raptor Group British Business Investments	B2B Telecom energy	Bathgate, United Kingdom	£24.0m-£36.0m	£6.0m SERIES A	Apr 2025
Wsense	Axon Partners Group CDP Venture Capital Fincantieri Blue Ocean Partners RunwayFBU	B2B Telecom semiconductors	Rome, Italy	€45m	€7.2m EARLY VC	Apr 2025
Next Generation Robotics	CDP Venture Capital Simest Pariter Partners AVM Gestioni Kilometro Rosso	B2B robotics	San Giuliano Terme, Italy	€18.0m-€27.0m	€4.5m SERIES A	Apr 2025
RTDT Laboratories	Rockstrat Swisscom Ventures BackBone Ventures Kickfund	B2B Energy Clean energy	Zurich, Switzerland	$16.0m - $24.0m	$4.0m SEED	Jul 2025
DriveSec	LIFTT Levante capital	B2B Security engineering and manufacturing equipment device security & antivirus	Turin, Italy	€12.0m - €18.0m	€3.0m EARLY VC	Feb 2025
Displaid	CDP Venture Capital Club degli Investitori Plug and Play ELIS- Centro Imprenditoria e innovazione Growth Capital	real estate construction	Milan, Italy	€4.8m - €7.2m	€1.2m SEED	Jul 2025

There are several innovation areas going from IoT monitoring and sensors for bridges, roads and railways, to the robotics for inspections, up to digital twins and mapping solutions. The segments linked to IoT cybersecurity (32 million dollars), inspection and monitoring drones (188 millions) and drone infrastructure (139 millions) are particularly relevant. Not to mention decarbonisation, maintenance management and electrical grid monitoring solutions, with significant investments in software and digital platforms.

This scenario confirms how infrastructure digitalisation is a strategic pillar towards more sustainable, safe and efficient models. The integration of advanced technologies – from IoT to artificial intelligence – not only improves infrastructure resilience but opens new business opportunities and cooperation between operators, startup and investors.

Here is the map of the Startups in Europe.

Areas	Combined funding $	Companies
Infrastructure monitoring - IoT and sensors for bridges, roads and trains	7.6M	2
Infrastructure monitoring - robotics monitoring for bridges, roads and trains	4.5M	1
Pipeline inspection	6.3M	4
Digital twins and mapping for infrastructure	7.4M	6
Underwater monitoring and communication	60M	7
IoT cybersecurity	32M	7
Drones and aerial vehicles for infrastructure inspection and monitoring	188M	14
Logistic drones for infrastructure	1.3M	2
Infrastructures for drones	139M	5
Maintenance management software	59M	4
Infrastructure monitoring - IoT & Sensors for other infrastructure	14M	2
Decarbonization planning software	15M	4
Grid: infrastructure monitoring and management	47M	3

Notes

1 https://www.istat.it/it/files/2011/03/UAN0146354InformazioniN7_Infrastrutture_in_Italia.pdf

2 D. Biehl, The Role of Infrastructure in Regional Development, 1991

3 D. Biehl, The Role of Infrastructure in Regional Development, 1991

4 D. Biehl, The Role of Infrastructure in Regional Development, 1991

5 https://www.ansfisa.gov.it/-/sistemi-di-gestione-della-sicurezza-delle-infrastrutture-stradaligestite-da-enti-localilavori-in-corso

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SAIDI= ∑(duration of non-programmed long outages)/number of customers in LV
Calculation features:

- only non-programmed long outages (duration > 3 minutes) are considered.
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- Financial costs: investment costs for infrastructure (networks, purification plants, reservoirs) and operating and maintenance costs.
- Environmental costs: costs related to resource protection, pollution prevention and environmental damage restoration.
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