WHITE PAPER

IoT-enabled corrosion sensors for predictive maintenance in structural health monitoring applications

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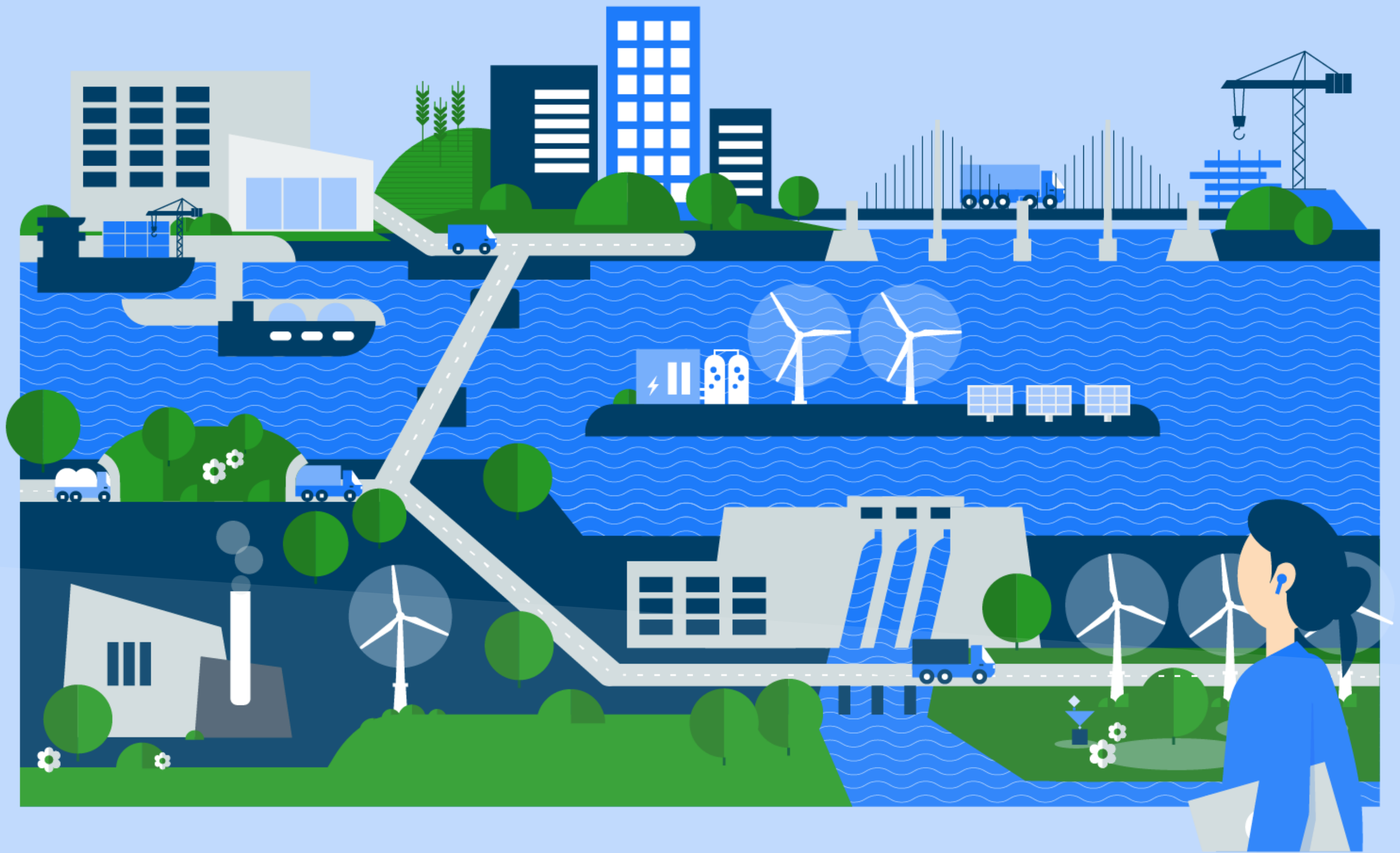

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Foreword

With the increasing demand for durability and safety in modern infrastructure, effective corrosion monitoring has become critical for structural health monitoring (SHM) applications (bridges, tunnels etc.) Proactive, effective monitoring helps prevent failures in reinforced concrete (RC) structures and minimises the economic burden, estimated at USD 2.5 trillion.

This white paper presents recent advancements in corrosion sensors, including physical, electrochemical and integrated sensor systems. Over the years, innovations such as cord-cutting, batteryless systems, energy harvesting, wireless data transfer and AI-driven predictive maintenance have been discussed for more sustainable infrastructure management. These developments not only provide engineers and researchers with new tools but also extend infrastructure lifespan, minimise costs, improve safety and help achieve sustainability goals, such as significantly reducing CO_2.

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1 Introduction

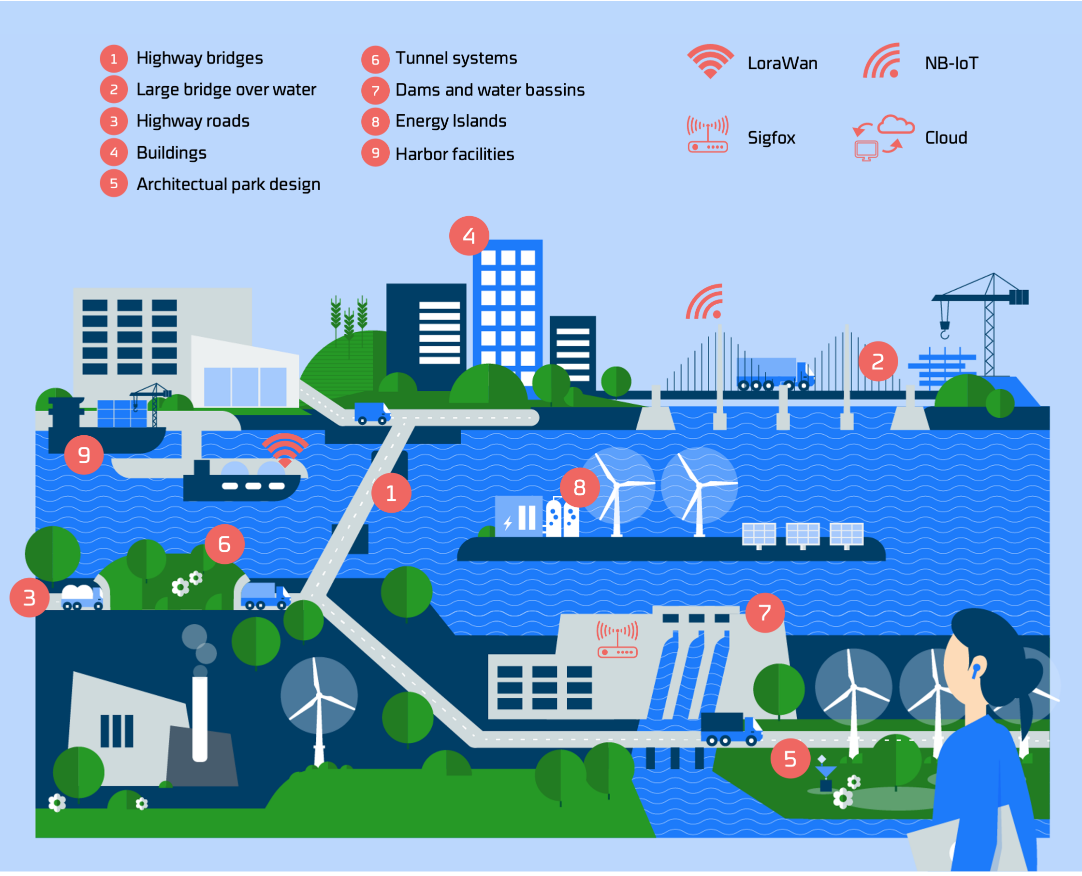


Figure 1a. Common type of infrastructures for embedding corrosion sensors in reinforced concrete for SHM applications.

Efforts to monitor structural corrosion and environmental corrosivity have been ongoing for decades, evolving with advancements in materials science and engineering. Observations of corrosion date back to ancient times, with figures such as Pliny the Elder noting the deterioration of iron. Significant improvements were made in the 18th and 19th centuries, with Robert Boyle's foundational work and Humphry Davy's sacrificial protection method using zinc.

By the early 20th century, corrosion sensors, such as electrical resistance and linear polarisation resistance, had emerged, particularly in the oil and gas industry. The mid-20th century introduced half-cell potential (HCP) measurements for non-destructive testing of reinforced concrete. Despite these advancements, notable bridge collapses like the Silver Bridge (1967) [1], Morandi Bridge (2018) [2], Fern Hollow Bridge (2022) [3] Carola Bridge (2024) [4] and Gambhira Bridge (2025) [5] highlight the critical need for effective corrosion monitoring.

Now, advancements have been made that enable real-time, accurate monitoring of corrosion. Today, smart sensors equipped with wireless technology, known as wireless sensor networks (WSN), and data analytics enable continuous monitoring and predictive maintenance across various industries, including infrastructure, oil and gas, aerospace and utilities.

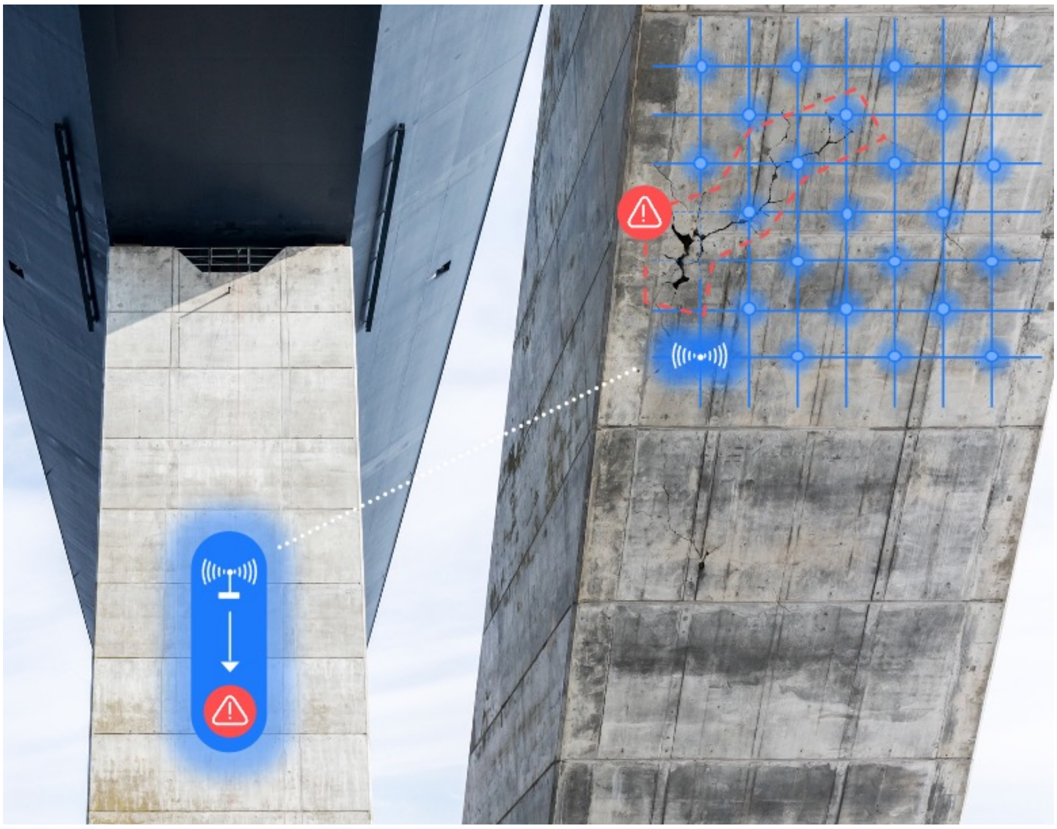


Figure 1b. Common type of infrastructures for embedding corrosion sensors in reinforced concrete for SHM applications.

Reinforced concrete (RC) is a fundamental material in modern construction and is widely used in industries, transportation and energy infrastructure. Its versatility allows for a broad range of architectural and technical designs, enabling the construction of structures of almost any size, shape or function [6]. However, the leading cause of early failure in concrete structures is due to corrosion of the reinforcement. Corrosion is commonly triggered by the chlorides present in salt water, antifreeze agents and chemical-induced loss of passivity, followed by the breaking and peeling of the protective layer, which weakens the bond between the steel and concrete, and eventually results in collapse [7]. Carbonation of concrete is another frequent contributor to steel reinforcement corrosion.

Currently, developed countries spend USD 2.5 trillion, which amounts to 3-5 % of the gross world product (GWP) [8] to manage the effects of steel reinforcement corrosion. Reducing these costs is a significant challenge for corrosion studies in the 21st century. Steel reinforcement corrosion in concrete structures occurs through an electrochemical reaction. Consequently, electrochemical methods [9] are the most widely used to determine the state of the reinforcement (whether it is passive or corroding) and to measure the corrosion rate. Physical methods [6] are also increasingly used, as they assess corrosion development through indirect indicators, such as changes in permeability, reduced adhesion at the interface of steel and concrete, and cracking resulting from a buildup of corrosion.

This white paper aims to assess the current literature on all identified corrosion sensors used for non-destructive monitoring systems for RC structures. We focus particularly on sensors designed for wireless data collection and transfer [10], which eliminates the need for engineers to be physically present near the concrete structures. The paper reviews all major types of sensors based on established principles, but does not delve into the detailed physicochemical principles behind each method. It covers developments from the past few years, including earlier approaches, available commercial products, newer sensors that are at various TRL levels, and stages of testing.

The later sections explore important design considerations, such as battery life, eliminating the need for cables (cord-cutting), and various energy harvesting technologies to keep sensors powered. We also compare embedded sensors versus retrofit options and look at why data logging, LoRa communication and cloud-based systems are becoming essential for managing data, in order to optimise the state of reinforced concrete structures.

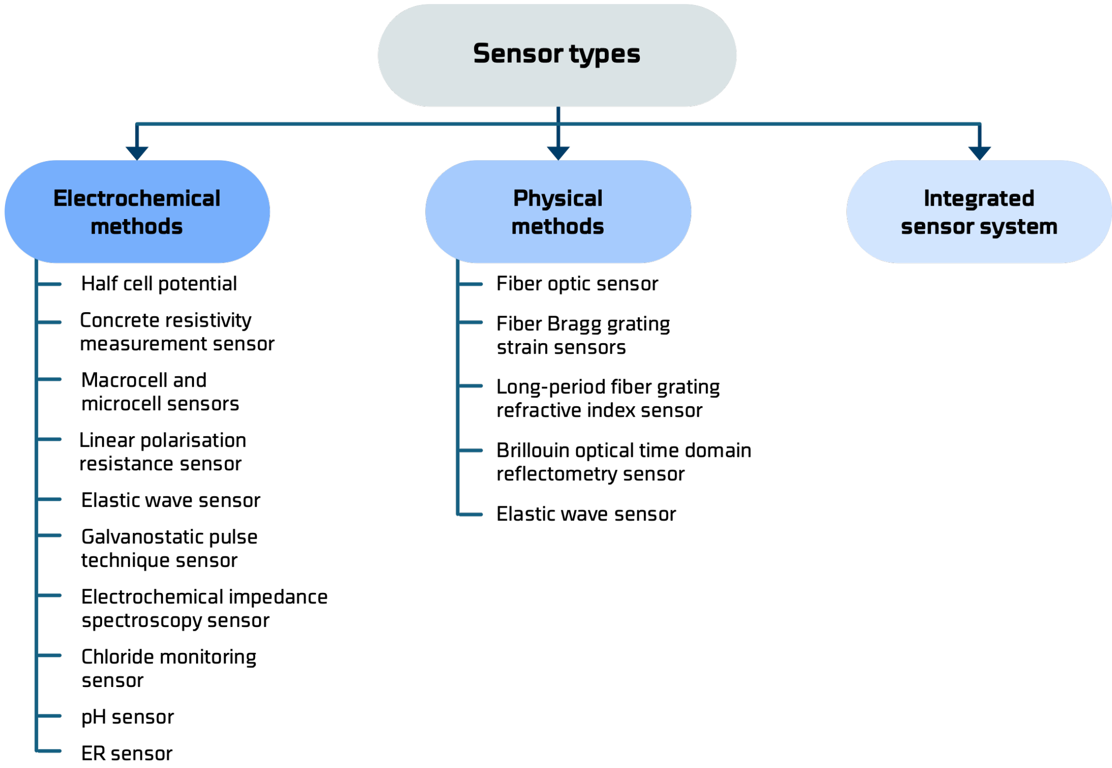


Figure 2. Categories of corrosion sensors.

A. Electrochemical methods

01. Half cell potential sensor

Function
Measures the potential difference between a reference electrode and the concrete reinforcing steel to assess the likelihood of corrosion.

Advantages
Non-destructive, easy to use, provide early warning, easy to install and designed for long-term operation of 20-25 years.

Disadvantages
Only suggest the potential for corrosion, not the actual corrosion rate.

02. Concrete resistivity measurement sensor

Function
Measure the electrical resistivity of concrete, which correlates to its moisture level and the likelihood of corrosion.

Advantages
Non-destructive and provide valuable insights into concrete quality.

Disadvantages
Measurements can be affected by temperature and moisture alterations.

03. Macrocell and microcell sensors

Function
Measure the flow of current between different areas of a metal surface to determine the corrosion rate.

Advantages
Well-suited for harsh environments and effective for long-term monitoring.

Disadvantages
Regular calibration required. Sensitive to temperature fluctuations and electrical noise.

04. Linear polarization resistance sensors

Function
Assess the polarisation resistance of a metal surface to estimate the corrosion rate.

Advantages
Offer high sensitivity, enable real-time monitoring and are easy to install.

Disadvantages
Regular calibration required. Sensitive to environmental fluctuations.

05. Galvanostatic pulse technique sensors

Function
A small current pulse is applied in a GPT sensor to the reinforcing steel, and the resulting potential is measured to assess the level of corrosion.

Advantages
Fast and non-destructive. Offer information on corrosion rate.

Disadvantages
Require specialised equipment. Affected by the thickness of the concrete cover.

06. Electrochemical impedance spectroscopy sensors

Function
Assess the corrosion rate by evaluating the impedance of the metal surface.

Advantages
Highly accurate and suited for various environmental conditions.

Disadvantages
Expensive and require specialised tools, equipment and technical expertise.

07. Chloride monitoring sensors

Function
Determine the presence and amount of chloride ions, which are a key contributor to corrosion in RC structures.

Advantages
Offer early detection of corrosion, which is caused by chloride.

Disadvantages
Calibration is difficult once cast in, and the service life is limited to a few years.

08. pH sensors

Function
Track the pH level of concrete, which impacts the passivation layer on reinforcing steel.

Advantages
Provide detailed information and insights into the concrete alkalinity.

Disadvantages
Affected by the content of moisture. Regular calibration is required. They are suitable only for short-term measurements in concrete.

09. Electrical resistance sensors

Function
Determine the changes in the metallic resistance that is exposed to the corrosive environment. As the corrosion of the metal increases, its area is reduced, which increases resistance.

Advantages
Suitable for hazardous environments. Provides early detection of corrosion.

Disadvantages
Often require calibration, and response time is slow.

B. Physical methods

01. Fibre optic sensors

Function
Utilise fibre optics to identify environmental changes that show corrosion.

Advantages
Highly precise, resistant to electromagnetic interference and ideal for long-term monitoring

Disadvantages
Complex installation process, expensive and require specialised equipment.

02. Fibre Bragg grating strain sensors

Function
Detect structural strains by identifying changes in the wavelength of light reflected by a fibre Bragg grating.

Advantages
Provide high accuracy and are highly immune to electromagnetic interference, corrosion and chemical degradation.

Disadvantages
High cost, fragile and thermally sensitive. Require specialised installation and handling equipment.

03. Long-period fibre grating refractive index sensors

Function
Measure changes in the surrounding medium's refractive index, which can indicate corrosion.

Advantages
Highly sensitive, resistant to EMI and do not need complex fabrication.

Disadvantages
Mechanically fragile, sensitive and have a limited range.

04. Brillouin optical time domain reflectometry sensors

Function
Utilise Brillouin scattering to identify strain changes and temperature differences along the length of fibre optic cables.

Advantages
Can monitor for long ranges with high accuracy.

Disadvantages
Expensive, and data interpretation is complex.

05. Elastic wave sensors

Function
Detect the elastic wave propagation generated by the cracks of corrosion.

Advantages
Non-destructive, and help identify corrosion at an early stage.

Disadvantages
Costly, and analysing and interpreting data can be complex.

C. Integrated sensor systems

01.

Function
Integrate multiple sensors to help provide detailed monitoring data for corrosion. This comprehensive solution helps provide a clear picture of the corrosion process and its monitoring.

Advantages
Combining different sensors improves accuracy and helps identify early detection signs.

Disadvantages
Increase cost and complicate the installation and maintenance of multiple sensors.

State-of-the-art comparison

A comparison of different corrosion sensors and their detailed specifications is presented in Table 1.

Ref.	Sensor	Company name	Parameter measured	Resolu-tion	Range	Corr. detect.	Acc.	Temp. range
[11]	Half-cell potential sensors	Profometer PM8500 / Corromap ERE20	Potential	±1 mV	-3000 to +3000 mV	Indirect	±0.5 mV	-10 to +50 °C
	Advantage: Non-destructive, highly sensitive.							
	Disadvantage: Complex data interpretation, higher cost.							
[12]	LPR and ZRA sensors	Pyxis Lab CR300 / Protector	Corrosion rate	0.001 MPY	0.001-10,000 MPY	Direct	N/A	-20 to +50 °C
	Advantage: Real-time monitoring, easy to operate.							
	Disadvantage: Environmental restrictions require regular maintenance.							
[13]	Galvanic sensors	CS350M / Corromap	Potential / Corrosion rate	10 μV (>100Hz), 3 μV (<10Hz)	±10V	Indirect	0.1% ×full range ±1mV	N/A
	Advantage: Quick measurement, suitable for complex environments.							
	Disadvantage: Higher operating temperature requires specialized equipment.							
[14]	Concrete resistivity sensors	Proceq Resistivity Resipod	Resistivity	0.2 kΩ·cm	1-1000 kΩ·cm	Indirect	±0.2 to ±2 kΩcm	N/A
	Advantage: Non-destructive, cost-effective.							
	Disadvantage: Highly sensitive to humidity and temperature.							
[15]	Fibre Bragg grating strain sensors	Smart Fibres Smart FBG	Strain	0.4 μstrain	± 9,000 μstrain	Indirect	N/A	-270 to +85 °C (Acrylate) / -270 to +300 °C (Polyimide)
	Advantage: Highly accurate, immune to EMI, and highly stable.							
	Disadvantage: Thermally sensitive and higher cost.							
[16]	Chloride ion sensors	SGX-CL2-5	Chlorine concentration	<0.01 ppm	0 - 5 ppm	Indirect	N/A	-20 to +40 °C
	Advantage: High sensitivity and fast response.							
	Disadvantage: Regular calibration is needed, and higher costs.							
[17]	pH sensors	Go Direct GDX-PH Sensor	pH level	0.01 pH	0-14 pH	Indirect	± 0.2 pH	5 to 80 °C
	Advantage: Suitable for various environmental conditions, highly accurate.							
	Disadvantage: Specialized tools are needed and have higher costs.							
[18]	Electrical resistance sensors	COSASCO®CUI Sensors	Resistance	N/A	N/A	Direct	N/A	Up to 200 °C
	Advantage: Early detection and cost savings.							
	Disadvantage: Environmental and installation errors.							
[19]	Micro/Macrocell sensors, FORCE Technology	CorroWatch / CorroRisk	Potential	1 mV / 1uA	± 2000 mV	Indirect	N/A	-10 to +40 °C
	Advantage: High precision and accuracy.							
	Disadvantage: Calibration and maintenance are required.							

Abbreviations: Abbreviations: LPR = Linear Polarization Resistance; ZRA = Zero Resistance Ammeter; Acc. = Accuracy.

Table 1. State-of-the-art comparison for different corrosion sensors.

2 Battery-powered sensors

Traditionally, corrosion sensors have relied on batteries to supply the required power for continuous monitoring and transmission of data. Because these sensors are commonly placed in inaccessible or hard-to-reach locations, connecting them to a wired power supply is either impossible or impractical. Using batteries allows the sensors to operate independently, enabling long-term data collection and transmission without the need for frequent maintenance [20].

However, relying on batteries comes with several challenges:

- **Maintenance:** Regular battery replacement is necessary, which can be time-consuming and expensive, particularly in large-scale installations.
- **Environmental concerns:** Disposing of used batteries can negatively impact the environment.
- **Limited lifespan:** Batteries have a finite life, which may restrict the overall operational longevity of the sensors. Moreover, significant temperature variation will further reduce the lifetime.

3 Cord-cutting

Consumers are increasingly shifting away from traditional cable TV to more flexible streaming options. A similar shift is occurring in corrosion sensors, where battery and corrosion sensors are transitioning from wired connections to wireless technologies.

The transition from wire to cord-cutting devices offers several advantages; a few are explained here:

- **Real-time monitoring:** Wireless sensors facilitate real-time monitoring of battery performance (including charge, discharge and temperature) or corrosion detection in critical infrastructures, eliminating the need for cumbersome physical wiring. Cord-cutting offers the flexibility to watch content on any device.
- **Improved flexibility:** Wireless and corrosion sensors enable engineers and technicians to remotely monitor battery health or corrosion levels.
- **Increased reliability and lifespan:** In harsh environments where battery systems or metal structures (such as bridges, pipelines, or aircraft) are used, eliminating physical cords enhances system reliability and reduces corrosion-related issues, thereby extending the lifespan of the sensors as well as the infrastructure they monitor.

4 Energy Harvesting

Remarkably, recent advancements have focused on developing batteryless corrosion sensors to address existing challenges in power management.

- The advancements in energy harvesting include sensors that can now harvest energy from multiple sources in their environment, such as solar power, thermal gradients or vibrations.
- Harvesting energy from different sources allows the sensors to operate continuously without the need for batteries. By combining solar and wind, the energy supply becomes more reliable.
- Advances in electronics have led to the development of ultra-low-power circuits requiring minimal energy. These circuits can function with small amounts of energy harvested from the environment.
- Some sensors use wireless power transfer technologies to receive energy from a remote source, eliminating the need for onboard batteries.
- These self-powered sensors use innovations like piezoelectric materials, which generate electricity when mechanically stressed, enabling sensors to power themselves through natural movements or vibrations in their environment.

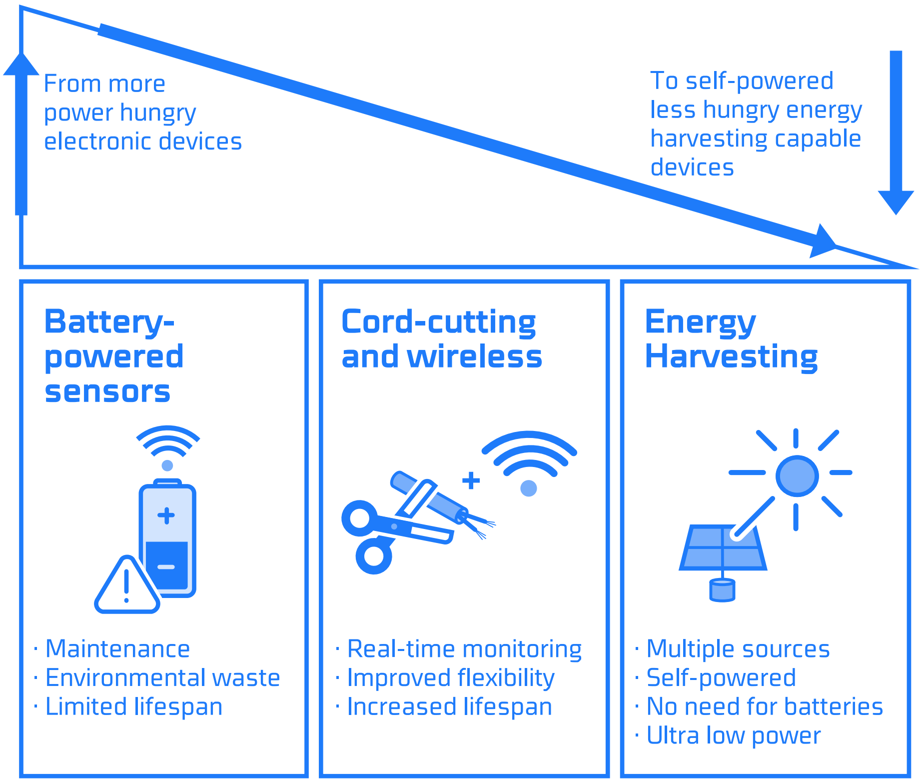


Figure 3. Trends from battery powered to battery-less corrosion sensors.

These improvements lower maintenance expenses, enhance environmental sustainability and increase both reliability and service life of corrosion monitoring systems, making them more appropriate for long-term and large-scale purposes [21] Figure 3 illustrates a shift from battery-powered to batteryless energy harvesting, featuring a more efficient and capable corrosion sensor. It should be noted that implementing and/or replacing a battery with an energy harvesting system is a process that should be considered carefully before implementation. The required power depends on the type and amount of data to be transmitted - for example, simple numerical data versus high-resolution images - and must be calculated carefully. In addition, the geographical location has a significant impact on the performance of the energy-harvesting system. For instance, solar panels in Denmark produce far less energy than those in California.

Moving to self-powered wireless sensors is more than a technical upgrade - it is a financial game-changer in cost savings. Cutting the wires can slash the cost of installing a single offshore sensor by up to USD 10,000 [22]. Retrofitting a power plant, installation costs drop by as much as 60 % [23]. Real-world deployments prove that a small sensor network can save 76 % over five years compared to traditional wired systems [24]. In modern building projects, this shift reduces total project costs by nearly 20 %[25]. This is tangible and proven ROI, turning capital expenditure into long-term value.

5 Embedded vs retrofit corrosion sensors

Key aspects and characteristics of embedded and retrofit corrosion sensors are shown in Figure 4. One important note here is that embedded sensors are normally cast into a given reinforced concrete structure in random locations, prior to the completion of the entire construction. A retrofit corrosion sensor can be placed in selected areas, providing more crucial data on progressing corrosion at critical locations.

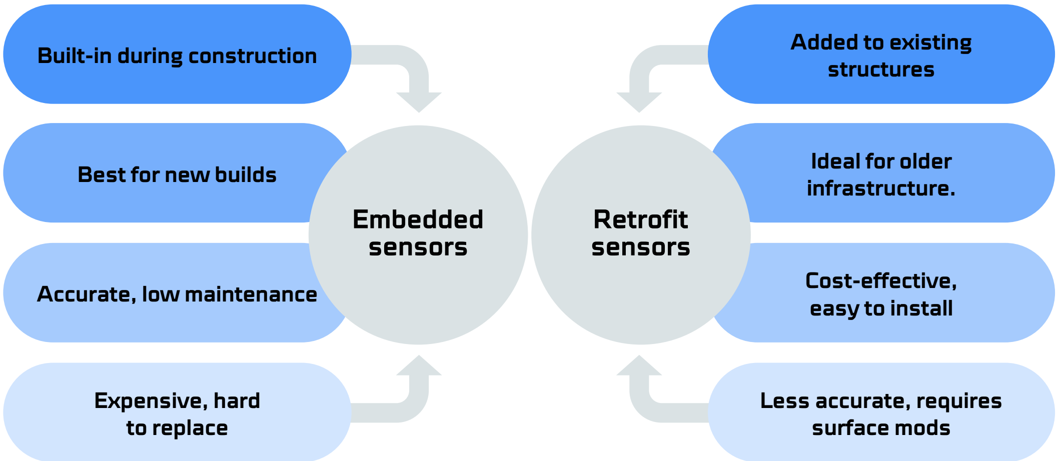


Figure 4. Key aspects and characteristic.

Table 2 outlines various attributes of both embedded and retrofit corrosion sensors.

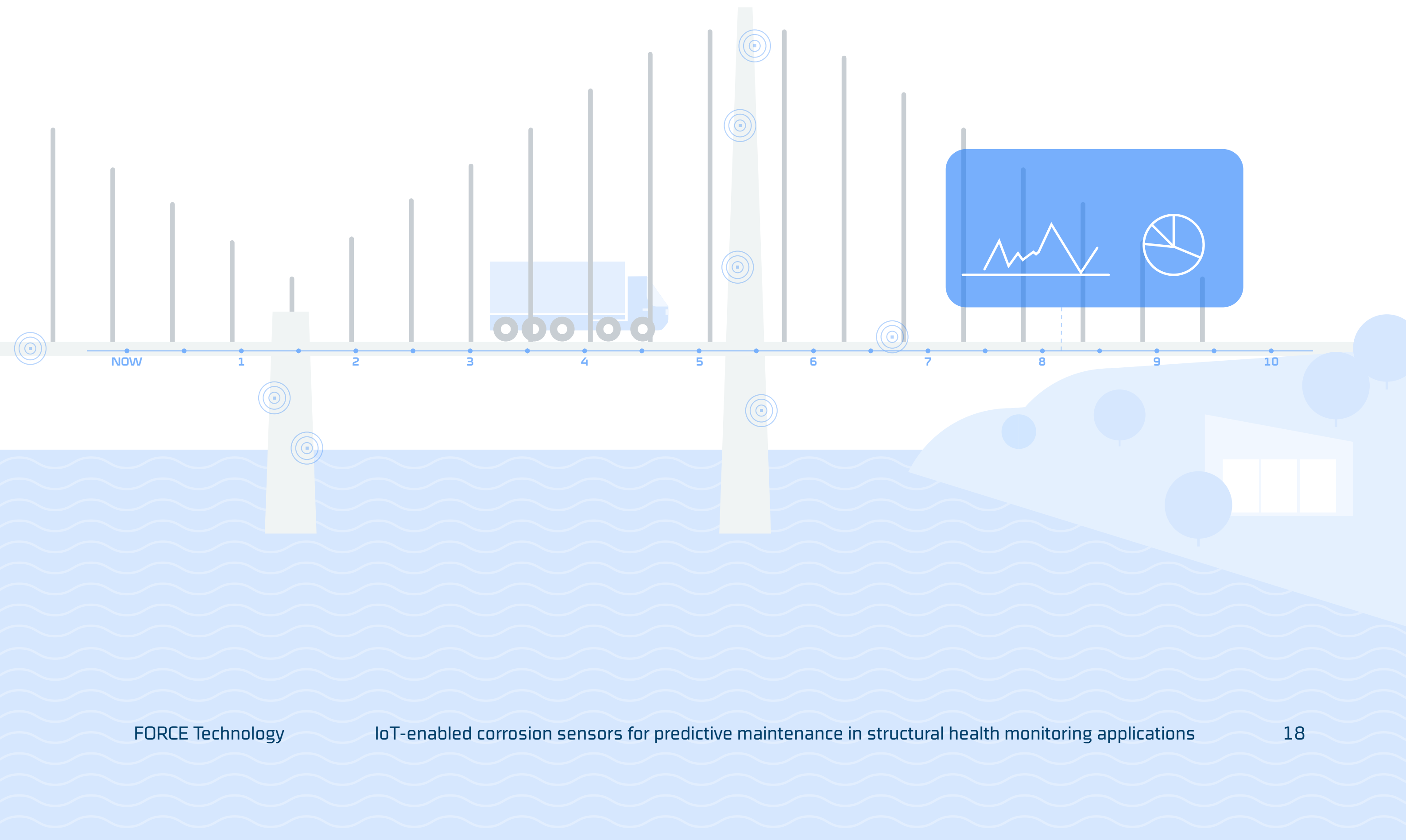
Sr#	Attribute	Embedded corrosion Sensors	Retrofit Corrosion Sensors
01	Installation	These sensors are integrated into the structure during the construction period.	These sensors are attached externally after the construction period.
02	Maintenance	These sensors need low maintenance but are not easy to access when installed.	These sensors are easier to replace and maintain because they are mounted externally.
03	Placement	These are positioned into the concrete, and they provide insight into internal corrosion.	These are positioned externally on the surface of the concrete structure to monitor outside conditions.
04	Integration	These sensors are being integrated into the new constructions.	These sensors are integrated into the already-built structure and therefore need some modifications.
05	Susceptibility	These sensors are more susceptible to external physical damage.	These sensors are more vulnerable and subject to temperature and moisture.
06	Monitoring	These sensors provide real-time and continuous data monitoring, which gives a comprehensive view of corrosion.	These sensors also provide real-time and continuous data monitoring but provide data of the surface-level elements.
07	Environmental impact	These sensors have a low impact on the external environment	These sensors are more prone to the external environment.
08	Data collection	These sensors collect data from the material directly, which offers accurate insights.	These sensors collect data from the external surface, which misses deeper insights into the material.

Table 2. Embedded vs retrofit corrosion sensors.

6 Datalogging

Data logging plays a crucial role in the monitoring of corrosion systems. It continuously records and monitors data from different sensors, including temperature, humidity and electrochemical systems. This ongoing collection of data is vital for monitoring corrosion progress over time. Maintaining, visualising and reacting to early signs of corrosion, marking and tracking changes, and recognising the environmental circumstances that impact material degradation are important for prolonging the lifespan of the structure. Data logging is necessary to ensure a comprehensive record of sensor readings, which is critical for well-timed and exact repair decisions.

- **Early detection:** Data logging helps track early signs of corrosion before they become a significant problem.
- **Continuous recording:** Data logging helps with continuous recording of parameters such as temperature and humidity.
- **Trend and pattern analysis:** Data logging helps in understanding the trend of corrosion progress over time and detecting certain patterns, such as correlation between temperature, humidity and other factors that might collectively impact the structure [26].
- **Environmental insights:** Data logging provides detailed data on how the environmental elements affect corrosion.



7 Communication (antenna)

LoRa communication is a wide area network that offers several benefits for sending a small amount of data over long distances. There are many competing technologies [27], such as Sigfox and NB-IoT, as shown in Figure 5. However, due to the battery-efficient nature of LoRa and moderate requirements of payload, it is usually a preferred choice for infrastructure monitoring applications [28] [29] [30].

In the context of corrosion sensors, because of limited power availability and the data packets being small, LoRa is well suited for this type of IoT device for remote monitoring.

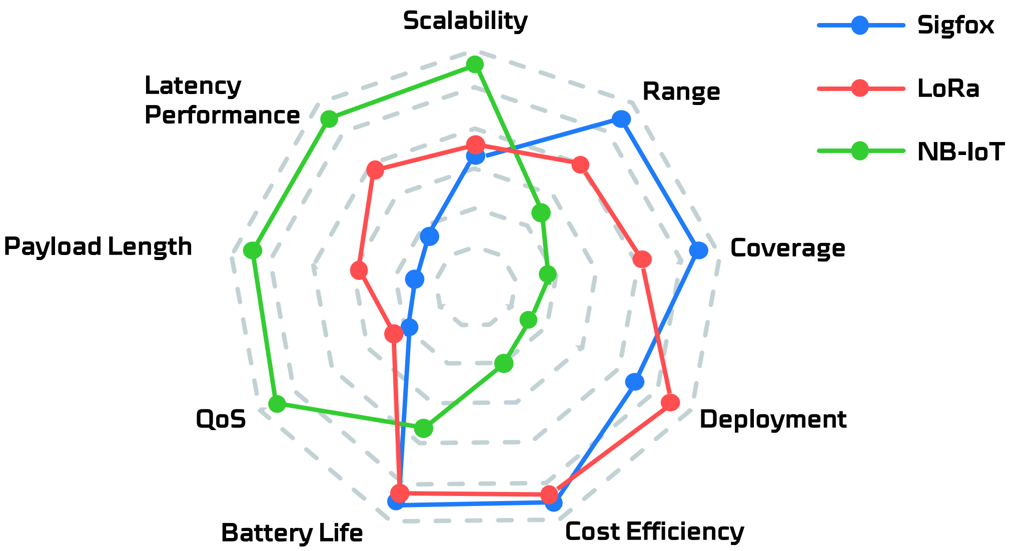


Figure 5. LoRa, Sigfox and NB-IoT comparison.

Advantages of using LoRa

There are several advantages of using LoRa for remote monitoring systems:

- LoRa has a capacity for low power consumption for remote monitoring of corrosion sensors because using a battery or energy harvesting always raises issues.
- It can communicate over long-range distances up to more than 10 km, depending on rural and urban locations.
- It transmits small data sets, making it more suitable for periodic updates of the data from a corrosion sensor.

To transmit data from corrosion sensors to a centralised station, LoRa wide area network technology is used, after which the data is forwarded to the cloud. However, the choice of antenna is also critical for reliable communication, since performance varies with placement, such as under a bridge. Depending on the antenna type, it is important to consider power efficiency, durability and the antenna's ability to cover the required transmission distance. It is always better to select the desired antenna depending on its placement.

Antennas are categorised into three different types:

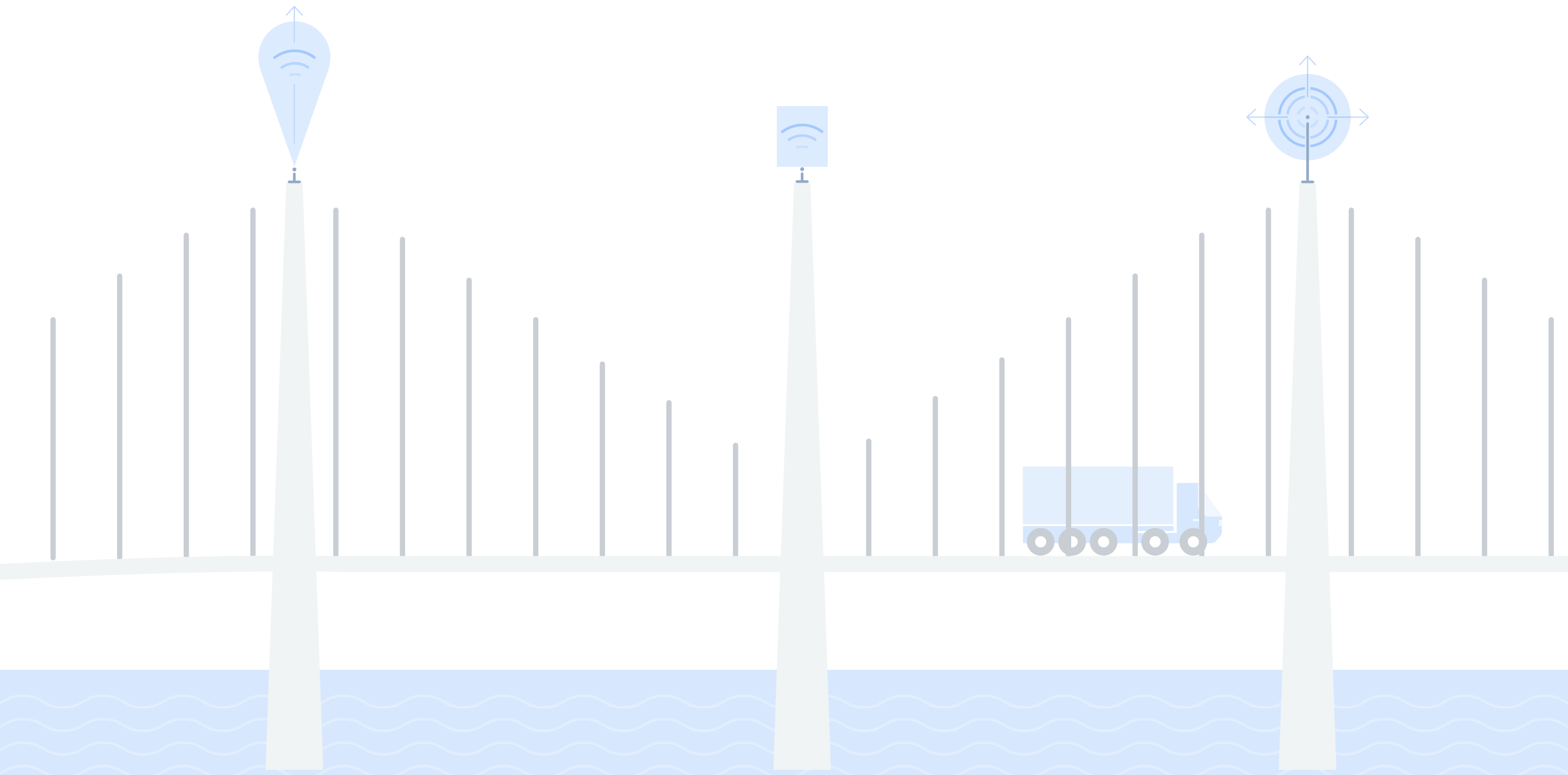
- Omnidirectional
- Directional
- Flat panel

Issues and challenges

- **Energy harvesting:** Energy-harvesting power management units harvest only small amounts of power. Therefore, for the data transmission, it is important to consider how much and how often data should be sent, so that the power is not consumed in a single large data burst [31] [32] [33].

- **Choice of antenna:** Transmission signals can be weakened due to attenuation and interference, since bridge structures made of metal tend to reflect and absorb LoRa signals. The correct choice and placement of the antenna are therefore essential.

- **Security concerns:** While LoRaWAN includes security features, vulnerabilities such as potential interception or spoofing, especially if not properly configured, can pose security risks in critical systems.



8 Cloud solution

The rise of the pay-as-you-go (PAYG) model for cloud resources has gained widespread popularity [34] [35] [36]. Some of the benefits of cloud computing are shown in Figure 6. The PAYG model has not only attracted millions of users globally but also seen new players offering their cloud products in the global market. The competition to offer new products to customers at affordable prices in various computing domains such as large-scale data processing, IoT, business intelligence, machine learning etc. has seen many companies switching to a pay-as-you-go model. These companies are using cloud products such as Infrastructure as a Service (IaaS), Platform as a Service (PaaS), Software as a Service (SaaS) etc. to accomplish a variety of tasks, Thus, sending, storing and processing corrosion sensor data in the cloud is not only resource-efficient - the availability of a variety of tools and services offered by various cloud providers makes a cloud-based solution very attractive.

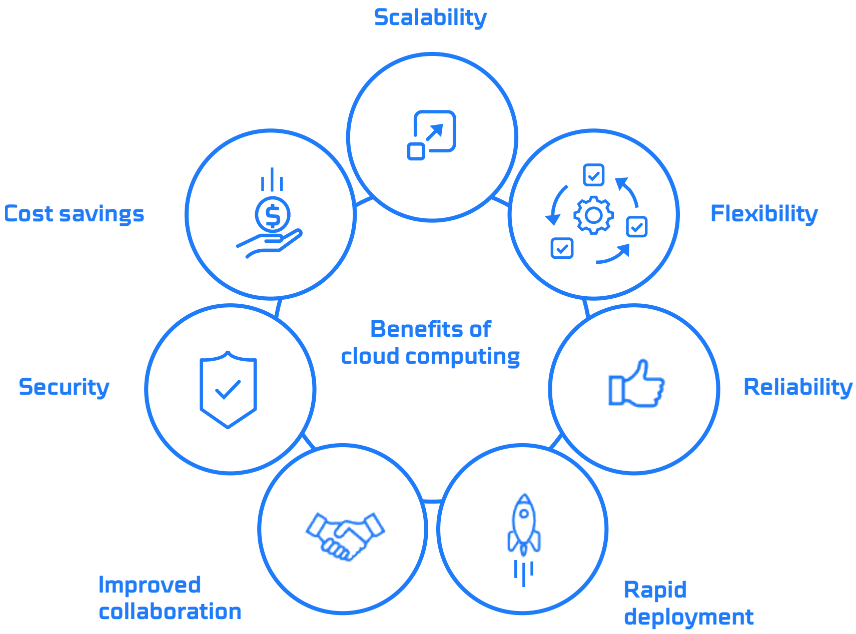


Figure 6. Benefits of data processing in cloud [33].

The implementation of a cloud-based solution for corrosion sensors offers several advantages, which include storage of the data in relational or NoSQL databases based on the size and application of the data, and building an application on top of that. This approach enables remote monitoring and control, allowing various sites to be managed from a centralised location. Furthermore, cloud storage not only guarantees that data is stored and protected, through features such as automatic backups, it also enables real-time data sharing and cooperation among different engineers, maintenance teams and strategy makers. Cloud solutions, due to their ease of use, scalability and flexibility, can be a valuable tool for integrating data, improving availability and enhancing teamwork, leading to more effective and efficient monitoring processes.

Some of the important features of cloud solutions for corrosion sensors are:

i. **Scalability:** Hardware and software resources in the cloud are scalable and can theoretically process data from an unlimited number of sensors, eliminating the limitations of on-premises systems. An important feature offered by the cloud infrastructure is dynamic scaling and descaling of processing and storage resources almost in real-time as the number of sensors or data increases. This elasticity ensures that removing or adding sensors is easy and does not require prior planning [37] [38] [39][40].

ii. **Real-time data processing:** Sometimes, it is important to receive frequent notifications or alerts to ensure that everything is under control and that nothing needs immediate attention. Cloud platforms support streaming analytics (e.g., AWS Kinesis, Azure Stream Analytics, Google Cloud Dataflow) for real-time monitoring and alerts. This allows fast decision-making needed for applications such as predictive maintenance, anomaly detection and closed-loop control systems [41] [42] [43].

iii. **Global accessibility:** It is possible to access, store and process sensor data on-prem. However, this requires proper tools and a security setup. Cloud infrastructure offers readily available storage and processing solutions to access data globally. This can be achieved using APIs, dashboards or mobile apps that provide connectivity to the data being processed and stored in the cloud storage solution.

iv. **Data storage:** Cost-effective storage solutions such as AWS S3, Azure Blob, Google Cloud Storage and time-series databases optimised for sensor data (e.g. InfluxDB and AWS Timestream) provide the low latency needed by the sensor applications. Moreover, data can be stored in the cloud in NoSQL databases. The non-relational nature of NoSQL solutions allows greater scalability. Managed database instances in the cloud ensure automatic backups and security, critical for continuous performance [44] [45].

v. **Analytics & machine learning integration:** The cloud solution provides libraries and frameworks that work out of the box for machine learning and data analytics. Thus, it reduces the time from idea to implementation. Cloud-native visualisation and dashboards help finding patterns of energy consumption, fault detection and other types of resource consumption.

vi. **Automatic updates & maintenance:** One major benefit of cloud solutions is that organisations do not need the expertise and resources required for server maintenance, firmware updates, backup and disaster recovery, since all of these tasks are usually carried out by the cloud infrastructure providers.

vii. **Integration with other cloud services:** Another advantage of using cloud platforms is ease of integration between internal frameworks and other cloud infrastructure providers. For example, streaming data received by AWS IoT Core using an MQTT broker can be stored in Amazon Simple Storage Service (Amazon S3). Similarly, streaming data can be received by Azure IoT Hub and then stored in an SQL Server database. Google Cloud IoT provides similar services, and data received using MQTT or HTTP can be stored in a Google-managed Postgres or MySQL [46] [47].

viii. **Cost efficiency:** Cloud platforms and applications follow a pay-as-you-go model, meaning organisations avoid upfront infrastructure costs. This shortens the time from idea to implementation, as there is no need to procure hardware, software or personnel to set up and maintain the infrastructure.

9 Data validation

In the corrosion sensors field, validation of data is critical for ensuring the precision, accuracy and reliability of sensor readings. This process involves detecting and resolving contradictions, errors or glitches in the data, which is critical for making informed findings regarding maintenance and repairs of the structure. By suggesting a trustworthy foundation for analysing corrosion trends and predicting future issues and problems, validated data proves to be vital. Maintaining data reliability and quality through validation is necessary for making precise and reliable findings, ultimately safeguarding the robustness, longevity and durability of the infrastructure. Figure 7 shows some of the most important dimensions of data quality that must be validated during the data validation process.

Poor-quality sensor data can lead to incorrect decisions and false alarms. Specifically for machine learning and analytics, poor-quality sensor data can result in "garbage in, garbage out" situations, as machine learning algorithms trained on unvalidated or corrupted data will learn incorrect patterns, leading to biased or inaccurate predictions [48] [49] [50].

10 AI & Machine Learning

Artificial intelligence (AI) and machine learning (ML) based algorithms and technologies are capable of analysing the large amount of data harvested from corrosion sensors to disclose patterns, developments and trends that may not be immediately obvious. These advanced technologies can predict and forecast when and where corrosion is likely to occur in the structure, aiding active maintenance approaches. Leveraging AI and ML algorithms and techniques, maintenance plans for concrete structures can be enhanced and optimised, which will reduce the danger of unexpected failures and extend the lifetime of their assets. Executing this, AI and ML are needed for converting new and raw data into operational insights, which assist in predictive maintenance and reduce the likelihood of sudden failures.

Furthermore, as mentioned before, to correctly predict the corrosion status and severity, it is important that the data used in the ML models and AI tools is properly validated and declared fit for purpose. Figure 7 illustrates the key dimensions of data quality that need to be verified. If necessary, automated and continuous data quality monitoring can be implemented using off-the-shelf tools or an in-house custom solution. An in-house custom implementation of data quality analysis, along with a possible fix, will be much more effective, as the relevant domain, constraints and quality dimensions are already known [51] [52] [53].

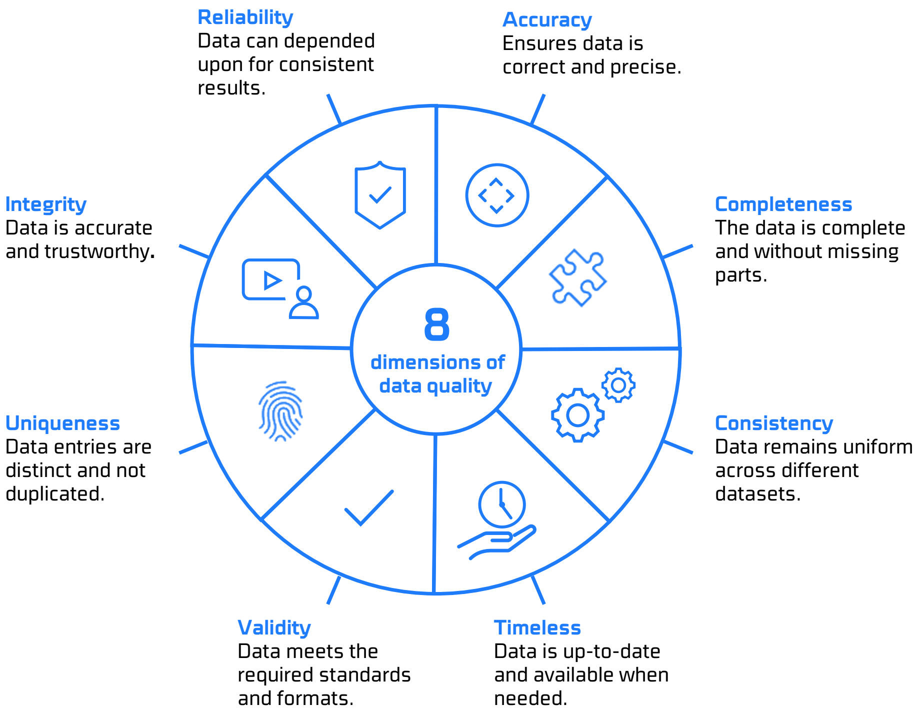


Figure 7. The 8 dimensions of data quality.

11 Predictive Maintenance

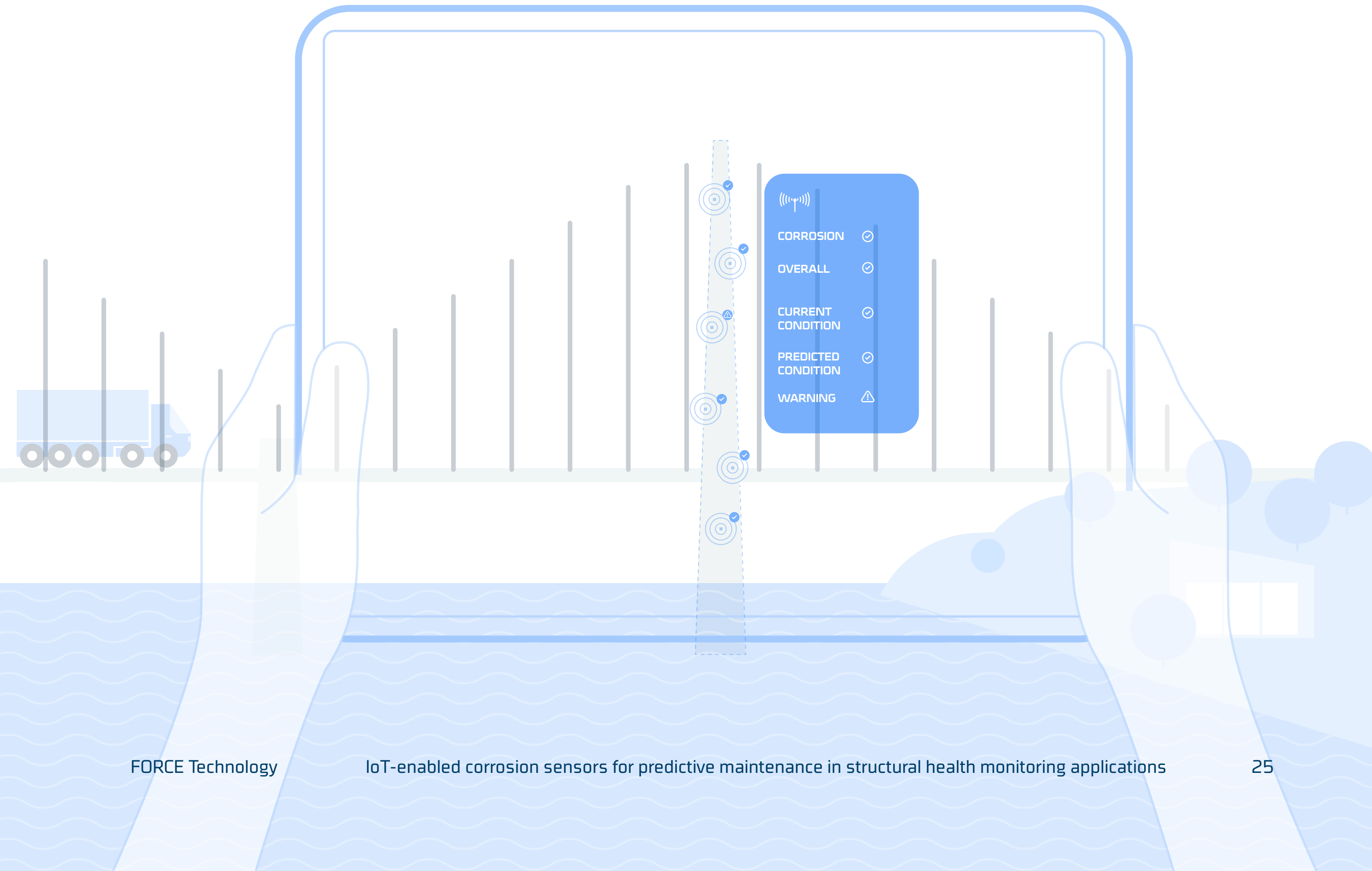
Maintenance plays a crucial role in ensuring the continuous operation of a system. There are various ways to maintain a system, such as preventive, corrective and predictive maintenance. Preventive maintenance is scheduled maintenance, performed at regular intervals (e.g. time-based or usage-based) to prevent failures and extend equipment lifespan. Corrective maintenance is performed after a failure has occurred to repair or restore equipment functionality. Predictive maintenance uses real-time data and machine learning to anticipate potential failures, allowing proactive maintenance before a breakdown occurs. Predictive maintenance for corrosion sensors uses insights from AI and ML to predict maintenance needs before they reach a critical phase. This approach emphasises conducting regular repair and maintenance based on the actual condition of the equipment rather than sticking to a fixed schedule. By predicting corrosion-related issues in advance, organisations can reduce downtime, lower repair expenditures and improve the safety, durability and reliability of their structures.

Incorporating predictive maintenance is necessary for addressing potential issues, eventually enhancing safety, minimising costs and improving the overall reliability of concrete structures. ML-based predictive maintenance is based on the quality and size of data. If the quality of data is not at the required level or there is not enough data to train ML models, companies can instead develop a rule-based system. Here, rules are used to trigger a specific condition that indicates the need for a particular type of maintenance. The set of rules in a rule-based predictive maintenance system requires a high degree of domain knowledge. It is only useful when there is a well-defined mapping between a predictive maintenance condition and the set of rules that can trigger and point to that condition [54] [55] [56].

12 Augmented Reality (AR)

Augmented reality can transform and revolutionise corrosion monitoring by offering real-time, interactive visions from different sensors, providing e.g. thickness loss, pitting and surface rust-related data, directly onto the physical structure using smart glasses or tablets. With this data, engineering maintenance teams can swiftly review equipment conditions without the need for manual inspections [57] [58] [59].

- AR also allows integration of digital twins on the infrastructure, highlighting corrosion-prone areas, comparing actual vs expected material degradation and visualising simulations of future corrosion progression. Integrating AR with digital twins can further enhance visualisation and predictive capabilities. AR-enabled devices can provide the technical team with a live vision of trends and track corrosion rates.
- After visualisation, teams can focus on which part of the structure they have to prioritise and inspect promptly.
- This methodology enhances streamlined maintenance, minimises cost and improves the safety of structural health monitoring applications.
- **Sensor fusion for AR:** By combining complementary sensor systems, higher accuracy and stability can be achieved. Sensor fusion also enables markerless AR, making it suitable for a wider range of environments, including outdoor settings. By combining, for example, cameras on drones for autonomous visual inspection of concrete surfaces with corrosion data from corrosion sensors, a new level of correlation can be achieved.



13 Conclusion

Corrosion monitoring for RC structures has seen significant innovations, offering new solutions to manage an expensive and widespread issue. This white paper has investigated a range of corrosion sensor types, from electrochemical and physical to integrated sensor systems, each sensor depicting unique advantages. Technological modernisations such as energy harvesting and wireless data transmission enable these sensors to overcome conventional challenges, especially those concerning power limitations and remote data accessibility.

Moreover, artificial intelligence and machine learning have elevated corrosion monitoring advancements, enabling active, predictive maintenance that can extend the lifespan of structures and improve safety and reliability. When combined with augmented reality (AR), these advancements support a new era of collaboration and efficient maintenance, providing real-time visions into critical infrastructure. Furthermore, with sensor fusion, new types of correlations can arise, using AI and ML. This is not possible today with just one sensor type. Using cameras on drones to capture images of a construction of interest, it may become possible to correlate these surface images with real corrosion sensor data, allowing AI and ML to predict the state of a construction by mere drone overflights.

With the help of these emerging technologies, corrosion monitoring is set to become not only more accurate and adaptive but also increasingly accessible and sustainable. This advancement is expected to save businesses billions in repair costs and substantially reduce the environmental impact of corrosion, ensuring that structures worldwide remain protected and healthy for generations to come.

By combining corrosion sensors with other sensors, cameras on drones, humidity measurements and similar inputs, a whole new level of correlation could be possible in the future. As the corrosion sensor becomes retrofittable and available as a low-cost CHIP solution, it will be possible to place e.g. 10,000 units on a large bridge construction. This will form a MESH network that feeds into a dashboard solution, based on e.g. a heatmap, which requires no technical insights from the monitoring part.

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