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*Research Article*

# Continuous Remote Monitoring in Hazardous Sites Using Sensor Technologies

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The deployment of a distributed point source monitoring system based on wireless sensor networks in an industrial site where dangerous substances are produced, used, and stored is described. Seven essential features, fundamental prerequisites for our estimating emissions method, were identified. The system, consisting of a wireless sensor network (WSN) using photoionisation detectors (PIDs), continuously monitors the volatile organic compound (VOC) concentration at a petrochemical plant on an unprecedented time/space scale. Internet connectivity is provided via TCP/IP over GPRS gateways in real time at a one-minute sampling rate, thus providing plant management and, if necessary, environmental authorities with an unprecedented tool for immediate warning in case critical events happen. The platform is organised into subnetworks, each including a gateway unit wirelessly connected to the WSN nodes. Environmental and process data are forwarded to a remote server and made available to authorized users through a rich user interface that provides data rendering in various formats, in addition to worldwide access to data. Furthermore, this system consists of an easily deployable stand-alone infrastructure with a high degree of scalability and reconfigurability, as well as minimal intrusiveness or obtrusiveness.

## 1. Introduction

Volatile organic compounds (VOCs) are widely used in industries as solvents or chemical intermediates. Unfortunately, they include components which, if present in the atmosphere, may represent a risk factor for human health. VOCs are also found as contaminants or as byproducts of many processes, that is, in combustion gas stacks and groundwater clean-up systems. Benzene, for example, is highly toxic beyond a time-weighted average (TWA) limit of 0.5 ppm (parts per million), as compared, for instance, with the TWA limit for gasoline which is in the range of 300 ppm. Detection of VOCs at sub-ppm levels is, thus, of paramount importance for human safety and, consequently, critical for industrial hygiene in hazardous environments.

The most commonly used portable field instruments for VOC detection are hand-held photo-ionisation detectors (PIDs), which can be fitted with prefilter tubes for detecting specific gases. The pluses are that PIDs are accurate to sub-ppm levels and measurements are fast, in the range of one or two minutes; for these thus hand-held PIDs are well-suited to field use. However, they have traditionally had two drawbacks: they require skilled personnel and they cannot provide continuous monitoring. Wireless hand-held PIDs have recently become available on the market, thus overcoming these two limitations, but they have a limited battery life, in addition to being relatively costly. This paper describes the implementation and field results of an end-to-end distributed monitoring system using just such VOC detectors, resulting in real-time analyses of gas concentrations in potentially hazardous sites on an unprecedented time/space scale [1].

Wireless sensor networks (WSNs), equipped with various gas sensors, have been actively used for air quality monitoring since the early 2000s [2–4]. WSNs have the advantage of offering full coverage of the monitored terrain by collecting measurements from redundant portions of the zone. WSNs are thus the ideal instrument for specific and efficient environmental VOC monitoring [5, 6].

This paper describes the implementation of a distributed network for precise VOC monitoring installed in a potentially hazardous environment in Italy. The system consists of a WSN infrastructure with nodes equipped with both microclimatic sensors as well as VOC detectors and fitted with TCP/IP over GPRS gateways which forward the sensor data via Internet to a remote server. A user interface then provides access to the data as well as offering various formats of data rendering. The continuous monitoring, using a unique blended wired/wireless configuration, of benzene emissions from a benzene storage tank is provided as a specific example of the network's usage. A prototype of this system was installed in the eni Polimeri Europa (PEM) chemical plant in Mantova, Italy, where it has been in continuous and unattended operation since April 2011. This pilot site is testing and assessing both the communications and the VOC detection technologies.

To avoid excavations, a stand-alone system, that is, one relying only on autonomous energy and connectivity resources, was designed and installed. In terms of energy requirements, the VOC detectors proved to be by far the greatest energy user, compared to the computational and communication units. So, to ensure a sustainable battery life for these units, efficient power management strategies were studied and implemented; moreover, the WSN elements were equipped with a secondary energy source, consisting of a photovoltaic panel.

This system represents several firsts. One important novelty is the stand-alone unattended long-term operation of communications in a potentially severely hostile environment. The proprietary communication protocols being used will not be discussed in this paper whose purpose is, instead, a general description of the system. Another breakthrough concerns the sensors; the PIDs' continuous power-on operation is made possible by calibration curve linearization and by their sub-ppm detection capability.

## 2. Emission Estimation Methods

Since estimating diffuse emissions is more difficult and complex than estimating piped emissions (e.g., by stack measurement), we first established what minimum features an ideal method, for licensing and enforcement purposes, must have. The fundamental criteria we pinpointed are:

(i) being inexpensive;

(ii) being suitable for leak detection (all compounds, all locations);

(iii) being suitable for all of the site's equipment and their phases of operation;

(iv) allowing real time estimation;

(v) allowing easy inspection for enforcement;

(vi) allowing depiction of the emissions over any time period;

(vii) allowing for reconfigurability.

A variety of methods for estimating diffuse emissions have been developed. These range from calculation to measurement, point measuring to remote sensing. Some are suited for leak detection, others for estimating annual emissions, and yet others for both of these functions. Below the main currently available methods are described, none of which, however, meets all of the criteria we identified as necessary for the ideal method.

*2.1. Distributed Point Sources.* The equipment for this method consists of standard air quality measuring devices. In order to cover all potential emission sources it is common practice to monitor several points; furthermore, instead of just fixed measuring points, mobile continuous sensors may be deployed. With the help of a "reverse" atmospheric dispersion model the emissions can be calculated from downwind air quality data combined with meteorological data. This method allows for estimating total emissions, however, it does not cover high plume emissions. Furthermore, the precise location of a leakage is hard to identify with this system.

*2.2. Fixed Beam (Open Path) Optical Absorption Method.* This method measures the absorption of an electromagnetic beam (IR and UV) by gases present in ambient air, based on the principle that specific gases will absorb light from known parts of the wavelength spectra. Depending on the amount absorbed between the beam source and the detector (coupled to a spectrometer and computer) the amounts of VOCs are calculated. High plume emissions, however, cannot be measured. Moreover, the exact location of a leakage is hard to find with this method as well.

*2.3. Differential Absorption LIDAR (DIAL).* Optical measuring techniques were further developed in the late nineties to overcome their limitations in pinpointing leakage and in detecting high-altitude leakage sources, resulting in DIAL (differential absorption LIDAR; LIDAR being light detection and ranging). In this system both the infrared laser beam source and the detector are located at the same end of the beam; the detector then picks up the signal from the small amount of light scattered from aerosol droplets or particles in the atmosphere. The main advantages of DIAL over fixed beam methods are that gas concentration is measured at all points along the path and no height limitations exist. Furthermore, it produces 2D and 3D maps of gas concentrations, making it possible to localise the emissions even within large industrial complexes. In other words, DIAL can estimate the total emission flux as well as localising (unexpected) leakage sources; in addition, it covers all potential emission sources (equipment, storage, loading/unloading, waste water system, etc.). However, both its accuracy of localisation as well as its differentiation between different chemical compounds are limited. Nevertheless, DIAL is an outstanding complement to standard point-by-point leak detection.

*2.4. Tracer Gas.* The tracer gas method consists of releasing a tracer gas (usually SF6) at different release areas and at various heights above the surface in the factory area and of measuring the VOC and tracer gas concentrations downwind of the factory via either portable syringe-based samplers or portable gas chromatographs. The emission rates of specific hydrocarbons can be estimated from simple flux reading, assuming nearby stationary wind conditions and with no significant atmospheric reactions or deposition of hydrocarbons or other release gases between the leakage points and the sampling points.

We weighed each of the above methods against the criteria our system required and opted for the distributed point system for the PEM Mantova site as it combines reasonable installation and maintenance costs, reconfigurability.

## 3. Our System Overview

To craft the system, first off suitable locations (both in terms of representativeness and expected impact) were identified along the perimeter of the industrial area, along with several internal sites where hazardous emissions might potentially occur. Owing to the extension and complexity of the Mantova plant, covering some 300 acres and featuring complex metallic infrastructures, it was decided to subdivide the area involved in the piloting into 7 different subareas. Each subarea is covered by a subnetwork consisting of a sink node unit (SNU) equipped with meteorological sensors, for recording wind speed/direction and relative air humidity/temperature (eni 1 to eni 7 in Figure 1). In addition, the eni 2 unit is further equipped with a rain gauge and a solar radiation sensor. An overview of the system deployed at Mantova is shown in Figure 1.

Each SNU is connected to one or more end node units (ENUs) equipped with VOC detectors (see Figure 2 for an example of a configuration), appropriately distributed across the plant's property. This modular approach allows the system to be expanded and/or reconfigured according to the specific monitoring requirements, while providing redundancy in case of failure of one or more SNUs.

The SNUs forward meteorological data, as well as VOC concentration data, to a remote server; as noted above, Internet connectivity is provided via TCP/IP over GPRS using a GSM mobile network. Wireless connectivity uses a UHF-ISM unlicensed band. Electrical power is provided by both primary sources (batteries) and secondary sources (photovoltaic cells), as mentioned above.

VOC concentration and weather/climatic data are updated every minute. This intensive sampling interval allows the evolution of gas concentrations to be accurately assessed. Furthermore, when all of the weather-climatic measurements are collated, they provide a map of the area's relative air humidity/temperature and wind speed/direction, which are crucial for providing accurate VOC-sensor read-out compensation [7]. The need for so many wind stations across the plant property is warranted by the turbulent wind distribution in that particular area, as can be observed by the different orientations of the blue arrows representing wind direction in Figure 1.

Three of the ENUs—eni 1, eni 2, and eni 3—were deployed along the perimeter of the plant to locally monitor VOC concentration while correlating it with wind speed and direction; the other seven were placed around the chemical plant and in close proximity of the pipeline, which are possible sources of VOC emissions. In fact, potential sources of VOC emissions in the plant are in easily identified areas, such as the chemical plant and the benzene tanks. The chemical plant was surrounded with a high number (6) of VOC sensors, thus creating a virtual fence, capable of effectively evaluating VOC emission sources based on the concentration patterns detected around the plant.

Figure 2 shows the layout of two of the subnetworks, one deployed around the chemical plant and one near the pipeline. The subnetwork around the chemical plant, Figure 2(a), consists of two SNUs, eni 6 and eni 7, equipped with weather sensors (air/wind), each connected with three ENUs spaced tens of meters from each other. The subnetwork located in the pipeline area is shown in Figure 2(b). One of the two ENUs is located in close proximity to the end of the pipeline itself (nodo *4*), while the other (nodo *2*) is a bit further away. Sampling the VOC concentration at intervals of tens of meters allows the dispersion of VOC emissions to be evaluated; in addition, information about wind speed/direction allows the emission's source to be identified.

## 4. The VOC Detector

The VOC detector is a key element for the monitoring system's functionality. For this application two criteria were considered mandatory. The first is that the VOC detector must be operated in diffusion mode, thereby avoiding pumps or microfluid devices which would increase the energy requirements and make maintainability issues more critical. The second criterion was that the system should be able to operate in the very low part per billion (ppb) range, with a minimum detectable level (MDL) of some 2.5 ppb with a ±5% accuracy in the 2.5 to 1000 ppb range, which represents the range of expected VOC concentrations. Another requirement was operating at one-minute intervals.

The PID fulfills most of the above requirements. Two major issues were identified, however, which potentially impact efficient use of the PID in our system. The first was that in the low ppb range the calibration curve of the PID shows a marked nonlinearity; this would require an individualized meticulous multipoint calibration involving higher costs and complexity. The second issue was that, when operated in free diffusion mode at low ppb and after a certain time in power-off, the detector required a stabilisation time of dozens of minutes, hence it would not be able to operate at our required one-minute intervals.

Since both of the above-mentioned limitations are intrinsically related to the PID's physical behaviour, this

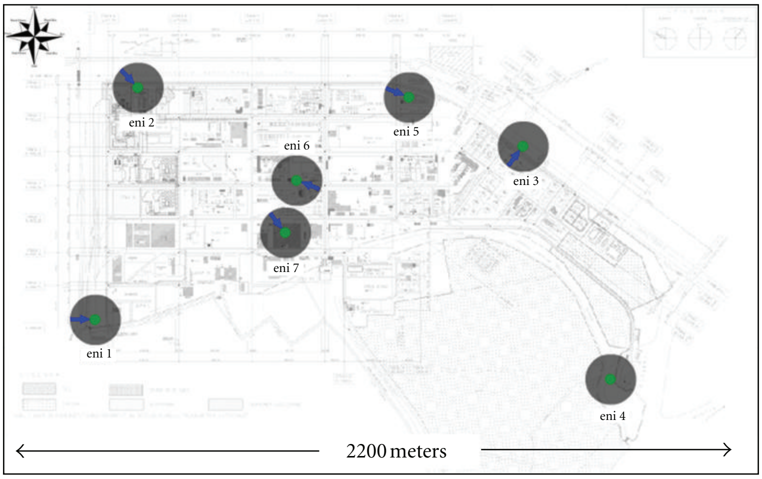
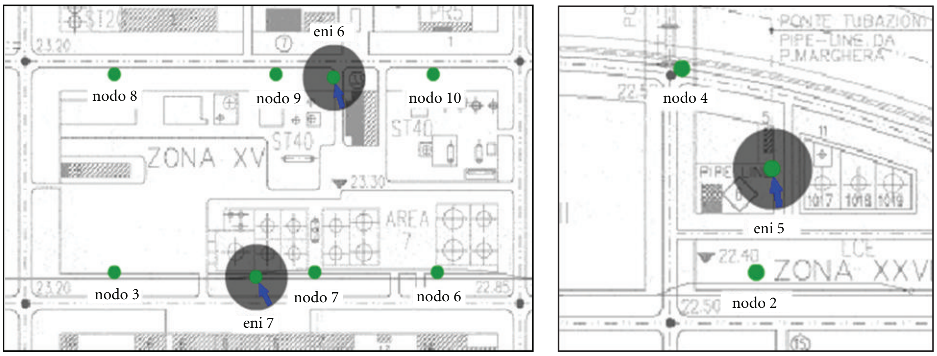



Figure 1: Installation overview. The grey circles indicate the position of each SNU; the blue arrows show wind direction.




(a) (b)

Figure 2: Closeups of SNU and ENU deployment around one of the chemical plants (a) and the pipeline (b). Maps are oriented according to the plant's axes rather than cardinal directions.

was carefully investigated and a behavioural model of the PID was developed to explain these phenomena. To resolve the nonlinearity, a mathematical expression of the PID calibration curve was derived [8]. Accordingly, the PID calibration procedure was adjusted to measure only two parameters: the zero gas voltage and the detector sensitivity in mV/ppm.

The second problem was the stabilisation time required to achieve a stable read-out time in diffusion mode at low concentrations. Originally our system requirements called for a minimum VOC data sampling interval of at least fifteen minutes. This would have had the additional advantage of prolonging the PID's battery life and maintenance, keeping costs down, However, discontinuously operating the PID results in stabilisation times of dozens of minutes in order to get a reliable PID read-out, which conflicts with the system requirement of sampling VOC concentrations in real time. In order to read very low VOC concentration levels in diffusion mode, however, the PIDs have to be continuously powered-on, consuming about 35 mA. Comparing the advantages of the two operation modes, the benefits of discontinuous operation were marginal compared to the matchless advantage of the more time-intensive monitoring of VOC concentration provided by continuous power-on operation. Accordingly, it was decided to operate the VOC detectors continuously at one-minute data sampling, which would also meet our established criteria of real-time estimation. Furthermore, this decision proved to be very effective as some emission events at the plant show very rapid variation, which would be difficult to interpret based on ten-minute sampling rates.

## 5. Continuous Emission Monitoring at Benzene Storage Tanks

Storage tanks represent an important potential source of VOC emissions and probably account for a significant amount of the site's total diffuse emissions. Thus they need to be appropriately monitored. Emissions from tanks can vary significantly from tank to tank, according to their size, design, maintenance, liquid level, and properties, as well as whether the tank is filling, stable, or emptying. Wind speed can also have a substantial effect on tank emissions, particularly for floating roof tanks.

Benzene storage tanks on this site are of the floating roof type and are located in highly hazardous areas. In fact, the electrical equipment operating in those areas need a special safety certification which classifies each area according to European Directive 94/9/EC (referred to as ATEX, an acronym for the French "Atmosphères Explosibles"), regarding equipment and protective systems intended for use in potentially explosive atmospheres.

The PEM site's benzene storage tank is certified as ATEX Zone 0, which means it is an area where an explosive atmosphere is continuously present or present for long periods of time; hence, the sensors that are located in close proximity to benzene sources must meet ATEX Zone 0 requirements.

The layout of the benzene storage tank monitoring network (STMN) is displayed in Figure 3. The STMN consists of three VOC units, each equipped with a PID and a computational unit, serially interconnected by wires as well as connected to the wireless unit (WU), which provides power and wireless connectivity. The WU is then connected to the GPRS unit (eni 3 in Figure 1) which provides the Internet connectivity. The reason for choosing such a hybrid wired/wireless configuration is due to the VOC detector's energy needs.

As can be observed in Figure 3, the three VOC detectors are located in Zone 0, which requires a very high level of protection, while the WU, along with the power unit consisting of the battery and the photovoltaic panel, needed to meet the VOC detectors' high energy consumption, is located in the non-Zone 0 area. In fact, the VOC unit's current absorption of 35 mA calls for a primary energy source with at least 80 A h capacity for 60 days of continuous operation. This would mean replacing 3 batteries on the top of the storage tank, requiring skilled personnel, every two months. This was considered impractical and too costly. On the other hand, the option of equipping the unit with a secondary energy source, such as a photovoltaic panel, to prolong battery life, was dismissed as incompatible with the safety requirements of an ATEX Zone 0.

As a result, the hybrid configuration of Figure 3 was drawn up, placing the VOC units within Zone 0, yet the communication/power supply units outside of the hazardous area. This permits usage of a secondary energy source, while, at the same time, allowing easy replacement of the primary energy source.

## 6. The Communications Platform

The communications platform, described more in depth elsewhere [1], is able to support a scattered system of units collecting VOC emission data in real time, while offering a high degree of flexibility and scalability, so as to allow for adding other monitoring stations as needed. Furthermore, it provides reconfigurability, in terms of data acquisition strategies, while being more economically advantageous than traditional fixed monitoring stations.

A GSM mobile network solution featuring a proprietary TCP/IP protocol with DHCP provides Internet connectivity. Dynamic reconnectivity strategies provide efficient and reliable communication with the GSM base station. All the main communication parameters, such as IP address, IP port (server's and client's), APN, PIN code, and logic ID, can be remotely controlled. Wireless connectivity between SNUs and ENUs is performed in an unlicensed ISM UHF band (868 MHz).

*6.1. The Sink Node and Wireless Interface Units.* A block diagram of the SNU is represented in Figure 4(a). It consists of a GPRS antenna and a GPRS/EDGE quadriband modem, a sensor board, an I/O interface unit, and an ARM-9 microcontroller operating at 96 MHz. The system is based on an embedded architecture with a high degree of integration among the different subsystems. The unit is equipped with various interfaces, including LAN/Ethernet (IEEE 802.1) with TCP/IP protocols, USB ports, and RS485/RS422 standard interfaces. The sensor board has 8 analogue inputs and 2 digital inputs. The SNU is also equipped with a wireless interface (WI), shown in Figure 3(b), which provides connectivity with the ENUs.

The wireless interface (WI), Figure 4(b), provides short-range connectivity. It operates on a low-power, ISM UHF unlicensed band (868 MHz) with FSK modulation; moreover, it features proprietary hardware and communication protocols. Distinctive features of the unit are the integrated antenna, which is enclosed in the box for improved ruggedness, as well as a PA + LNA for a boosted link budget. The PA delivers 17 dB m to the antenna, while the receiver's noise figure was reduced to 3.5 dB, compared with the intrinsic 15 dB NF of the integrated transceiver. As a matter of fact, a connectivity range in line-of-sight in excess of 500 meters was obtained, with a reliable communication with a low BER, even in hostile EM environments.

The energy required for the unit's operation is provided by an 80 A h primary source and by a photovoltaic panel equipped with an intelligent voltage regulator. Owing to its prudent low-power design, the unit can be powered with a small (20 W) photovoltaic panel while maintaining continuous unattended operation.

Given the distance among the sink nodes and the hostile EM environment, implementing a multihop WSN would have been impractical, costly and troublesome in terms of quality of service; our solution, instead, has resulted in practically flawless performance, in terms of reliability, with only a very marginal extra cost.

*6.2. The EN Unit.* A block diagram of the ENU is shown in Figure 5; it consists of a WI, similar to that previously described, yet includes a VOC sensor board as well as a VOC detector. The acquisition/communication subsystem of the ENU is based on an ARM Cortex-M3 32-bit microcontroller, operating at 72 MHz, which provides the necessary computational capability on the limited power budget available.

To reduce the power requirement of the overall ENU subsystem, two different power supplies have been implemented: one for the microcontroller and one for the peripheral units. The microcontroller is able to connect/disconnect the

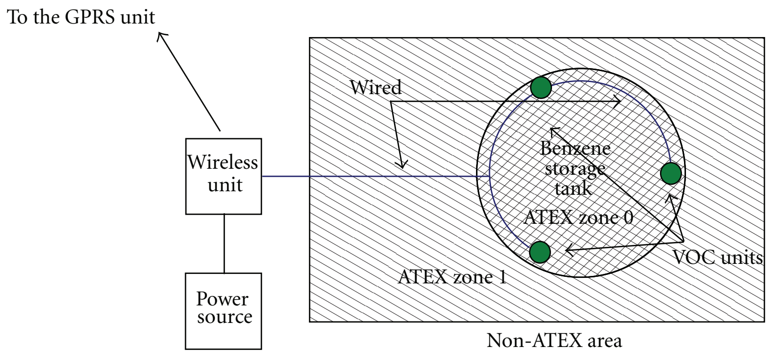



Figure 3: Scheme of the storage tank monitoring network (STMN).

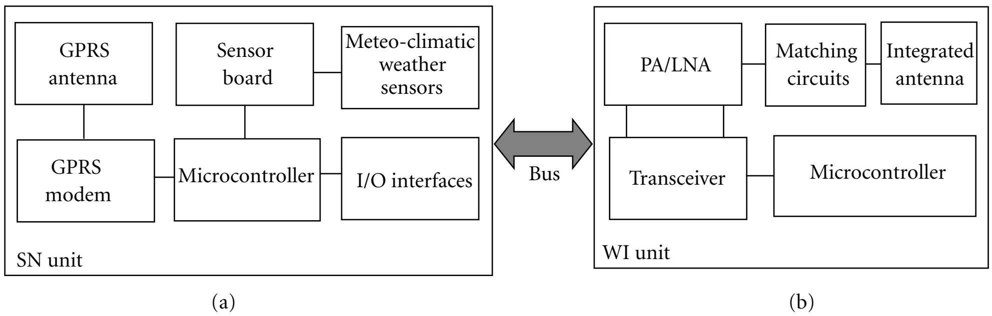



Figure 4: Block diagram of an SNU (a) and a WI unit (b).

peripheral units, thus preserving the local energy resources. The VOC detector subsystem in particular is powered by a dedicated switching voltage regulator; this provides a very stable and spike-free energy source, as required for proper operation of the VOC detector itself.

Communication between the ENU and the VOC detector board is based on an RS485 serial interface, providing high-level immunity to interference as well as bidirectional communication capability, which is needed for remote configuration/reconfiguration of the unit.

## 7. WSN Issues

*7.1. Network Structure and Routing Schemes.* Among the different alternatives, a hierarchical-based routing scheme was selected based on the particular nature of the installation: the extended area of the plant, the few critical areas of potential sources of emissions requiring dense deployment, and the highly uneven distribution of nodes over the area. A hierarchical-based routing scheme fit the projected deployment layout well. As said before, the installation was partitioned into subnetworks to be deployed around the critical sites, with one SNU for each individual subnetwork. In principle, wireless connectivity between the SNUs could have been implemented, using one specific SNU as a gateway to the Internet. This option, however, conflicted with at least two of the major requirements. The first is the need for redundancy in case of failure of the gateway unit; in this scenario, in fact, Internet connectivity would be lost, with consequent loss of the real-time updating capability, which is considered a mandatory requirement for the system. The second need which would not have been met is that of providing full connectivity among the individual SNUs under conditions where line-of-sight propagation was not guaranteed, due to the presence of such temporary obstacles as trucks or maintenance infrastructures. A multiple-GPRS gateway approach overcomes those limitations; even in the case of failure of one or more gateway units, Internet connectivity would be provided by the others still in operation, while the issue of the obstacles is circumvented. As for the wireless connectivity, a star configuration was preferred to a mesh configuration, given the limited number of nodes and the need to keep latency at a minimum.

*7.2. Protocols and WSN Services.* Two levels of communication protocols, in a mesh network topology, were implemented. The upper level handles communications between the SNs and the server; it uses a custom binary protocol on top of a TCP layer. This level was designed and calibrated for real-time bidirectional data exchange, where periodic signaling messages are sent from both sides. Since our sensor network necessitates a stable link, quick reconnection procedures for whenever broken links should occur, were especially important. To ensure minimal data loss, the SNs have nonvolatile data storage, as well as automatic data packet retransmission (with timestamps) after temporary downlink events. Furthermore, this design is well suited for low-power embedded platforms like ours, where limited memory and power resources are available.

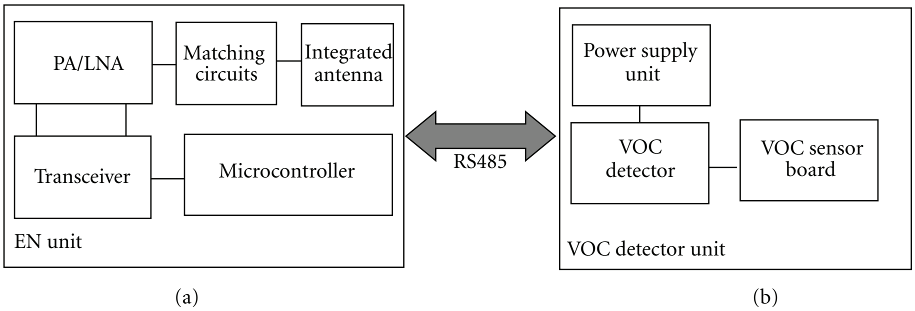



Figure 5: Block diagram of the ENU (a) and the VOC detector unit (b).

In fact, our protocol stack currently requires about 24 KB of flash memory (firmware) and 8 KB RAM.

The lower level, in contrast to the upper one, concerns the local data exchange between the network nodes. Here a cluster tree topology was employed; each node, which both transmits and receives data packets, is able to forward packets from the surrounding nodes when needed. In this specific application, the topology and routing schemes are based on an ID assigned to each EN unit, where the ID can be easily adjusted using selectors on the hardware board. This choice allows for easy support and maintenance, even when non-specialized operators have to install, reinstall, or serve one or more units.

## 8. Energy Budget Issues

Energy budget plays a key role in the maintainability of the WSN [9]. In our case this is made even more critical by the necessity for stand-alone operation, as well as due to periodic maintenance intervals in excess of four months. Since electrical energy from the plant could not be used, secondary sources had to be locally available; photovoltaic panels (PVP) fit the bill. The SNUs are almost all equipped with PVPs, as they have to support a number of functions, including connectivity and data collection from sensors. The ENUs, when equipped with low-energy sensors, have 3 to 5 years of battery life using primary sources [10]. However, in this system the ENUs have to support the power-hungry VOC sensors as well. For this reason, the ENUs are also equipped with PVPs.

*8.1. ENU Energy Budget.* The EN nodes have been fully deployed since July 2011; since that time we have noticed that the VOC sensors' energy budget predominates over that of the computational/communication unit. Since the PIDs used for reading the VOC concentration need to be continuously on to operate efficiently, this corresponds to a current draw of some 35 mA, corresponding to 840 mA h a day, more than twice the amount used by the communication/computational units, which consume some 360 mW a day. The ENU's primary source capacity is 60 A h, which provides more than 2 full months of continuous operation.

To enable the ENUs to rely fully on autonomous energy resources while providing continuous operation, a 5 W photovoltaic panel was integrated into the unit in order to supply the additional 360 mW average required power. The PVP, however, can fulfil the task only under ideal sunlight conditions, that is, in summer, but hardly at all in winter. Hence, the PVP power supply unit also has a charge regulator which was specifically designed to provide maximum energy transfer efficiency from the panel to the battery regardless of weather conditions. In conclusion, the secondary energy source plays a key role in ensuring the stand-alone and unattended operation of the communication platform.

As a concrete example, Figure 6 shows the battery voltage plots for the ENUs connected to SNUs 5 and 6. As can be observed, the ENUs exhibit quite satisfactory charge conditions, although ENU 4 (eni 5 nodo 4) shows a slightly lower voltage level, probably due to deployment in a partially shadowed area. The battery voltage remains above a 12.3 V value, with a slightly decreasing trend, possibly due to lower solar energy given the fact that the time period corresponds to the onset of autumn.

*8.2. SNU Energy Budget.* The SNUs were deployed at the PEM plant in the middle of April 2011. They have much higher energy requirements than the ENUs as they have to supply energy for both wireless connectivity and sensor operation (including meteorological sensor).

The average current draw is around 90 mA, corresponding to a power consumption of about 1 W. SNUs have superior primary and secondary resource capabilities, with a 2-month battery life relying on the primary source alone.

Figure 7 shows the battery voltage for the eni 2 to eni 7 SNUs; the eni 1 plot is missing as the chart can only represents 6 graphs in each diagram. As can be observed, all the units demonstrate a minimum voltage exceeding 12.3 V, which denotes a satisfactory charging state. In this period there is also a slight decrease in the minimum battery voltage value, showing an energy imbalance between the primary and secondary sources, mostly due to sunlight reduction, as in the graph for the ENUs.

Detailed information about charge status and trending are also available; Figure 8 gives an example of how the current drawn by or supplied to the battery is compared with charge status. As shown here, the energy balance keeps the battery voltage at a steady, satisfactory level. Extensive data logs and reports are available to help the maintenance team

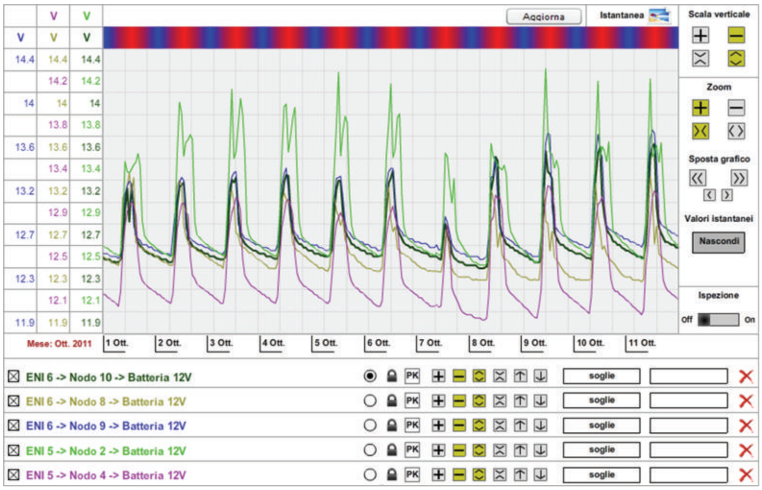



Figure 6: Battery voltage of the ENUs of the eni 6 and eni 5 subnetworks from October 1st to October 11th.

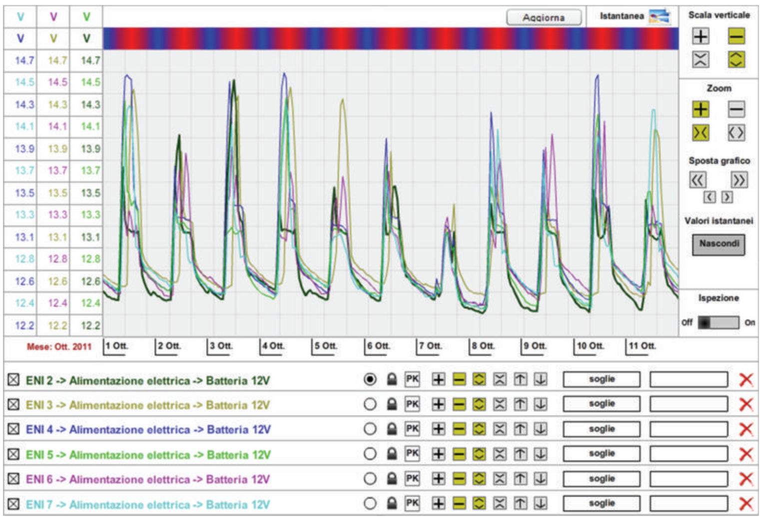



Figure 7: Battery voltage of SNUs 2 to 7 from October 1st to October 11th.

in evaluating any critical event or servicing required to keep the system in full operation.

*8.3. VOC Detector Energy Budget.* Continuous power-on operation requires a 35 mA h charge, which corresponds to about 2 months of full operation with a 60 A h primary energy source. However, as described above, this can be lengthened due to PVP integrated power. Furthermore, since the UV lamp's expected life is more than 6000 hours of continuous operation, that is, about four months, routine maintenance for the system—UV lamp replacement, PID refitting and battery replacement—can be planned on a four-month cycle.

## 9. Experimental Results

Data from the individual sensors deployed on the field can be directly accessed and presented in various formats. First, the data from the field is forwarded to a central database for storage; then, for effective data rendering the system offers a web-based interface, allowing us to process and view data in real time. There are several formats for displaying the main factors, such as weather information and VOC concentrations. However, it is also possible to access raw data, and generate summary reports relating to specific time periods and specific network areas. Furthermore, all monitored variables may be related to each other visually. Following are examples of the various formats the interface offers.

The overview map (Figure 9(a)) provides information about the entire network installed at the PEM plant. Each SNU is represented with a gray circle and a blue arrow indicating the wind direction. By selecting one of the circles (Figure 9(b)) a summary panel appears that lists the current temperature, humidity, wind speed and direction, as well as VOC concentrations over a daily, weekly, or monthly period. Minimum and maximum values of the day are also shown.

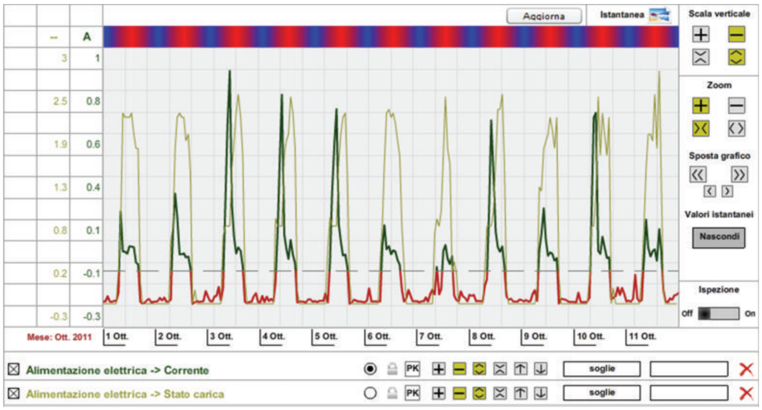
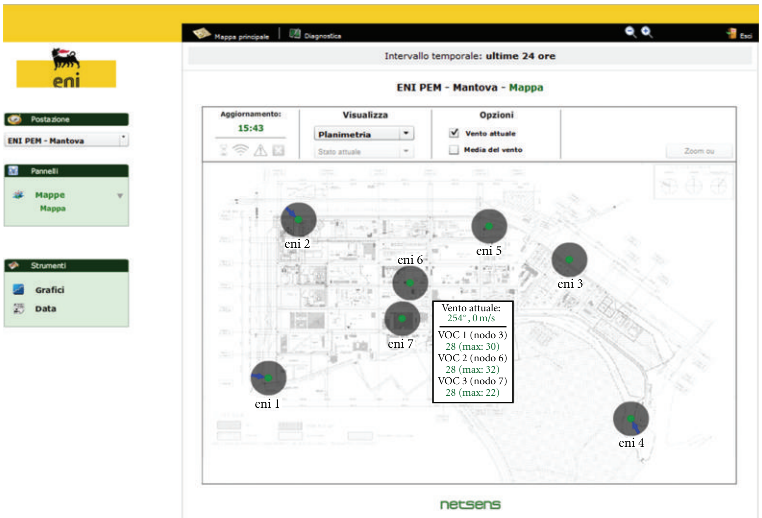
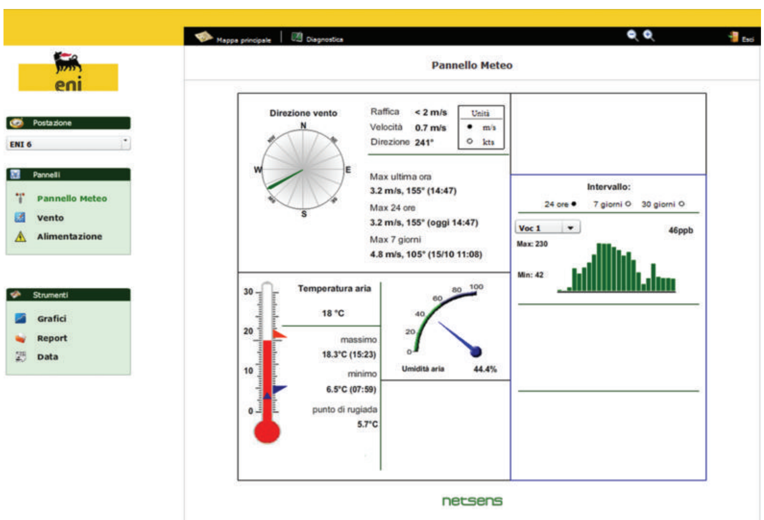



FIGURE 8: Current draw and charge status of SNU 1 from October 1st to October 11th.

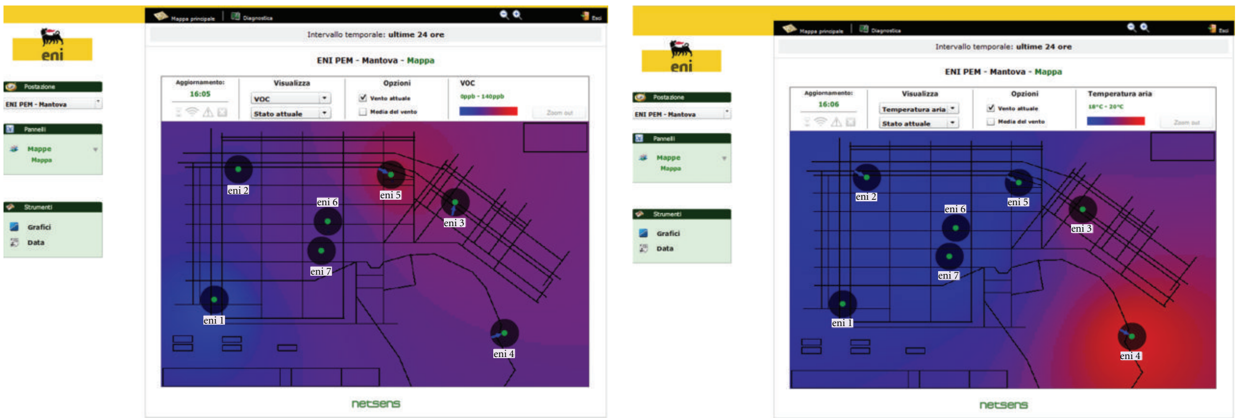



(a)




(b)

FIGURE 9: Examples of data rendering—installation map (a) and summary panel (b).




(a) (b)

Figure 10: Examples of data rendering—VOC concentration (a) and temperature distribution (b) across plant site.

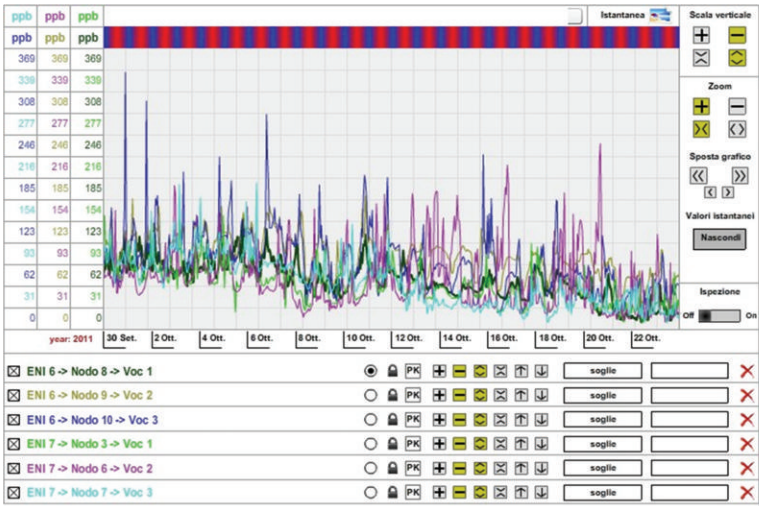



Figure 11: Example of data rendering—graph of VOC concentration in six detectors deployed around the chemical plant.

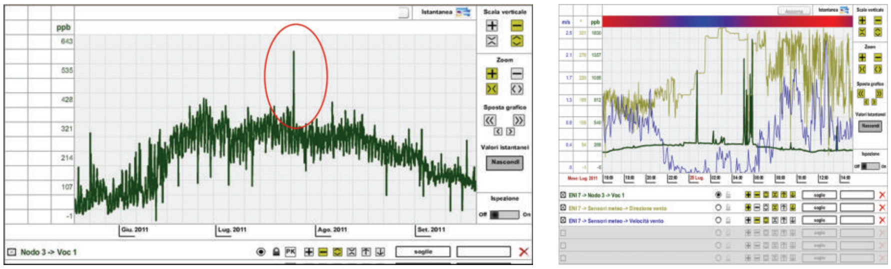
Figure 10 shows a different possible type of 2D representation of the VOC, (a), and climatic, (b), distribution over the plant.

These representations, obtained using an interpolation algorithm, are in pseudo-colour. Blue denotes a lower concentration/temperature, while red indicates a higher one. This format is particularly useful for quickly identifying quickly if there are any areas within the plant with high VOC concentrations and whether they are related to meteorological conditions. It should be emphasized that the choice of red was merely a chromatic one; it has absolutely no reference to any risky or critical condition.

An additional visual rendering of the data gathered by each sensor on the field can be obtained by opening the graphic panel window, see Figure 11. This panel allows anyone to display graphically the stored data in any time interval; up to six different and arbitrarily selected sensors can be represented in the same window, for analysis and comparison. The graph in Figure 11 shows the trend in VOC concentration values detected by the six PIDs deployed around the chemical plant over one month; the background values are similar to each other, demonstrating the effectiveness of the calibration procedure.

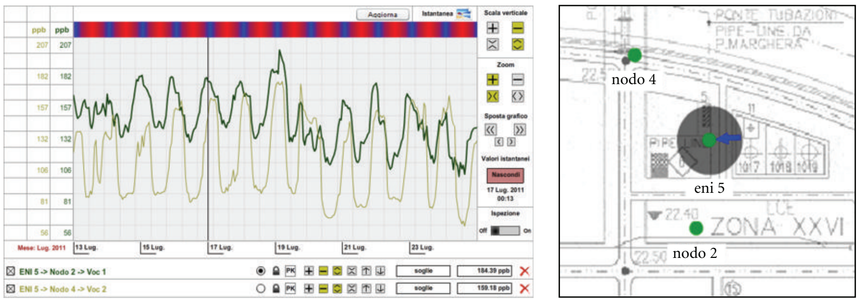
By selecting specific areas within the chart it is possible to further increase the details of the graph, allowing an easier interpretation of any short peak detected. In fact, thanks to the intensive 1-minute sample interval, the evolution of the concentration, along with other relevant weather parameters, can be accurately displayed. Moreover, a useful inspection tool allows users to quickly record min, max and mean values in any selected period.

Figure 12(a) shows VOC concentration readings over a long term (4 months) from a sensor positioned along the perimeter of the industrial area. As can be observed, the data reveals an increase in the background value during the summer, probably due to higher temperatures; in fact, the peak value (a concentration greater than 500 ppb), registered around July 25th, was due to meteorological conditions that affected the dispersion of pollutants, as seen in Figure 12(b). This graph combines the peak VOC value with a very




(a) (b)

Figure 12: Graph of VOC concentration in the long term (a) and correlation between VOC and wind speed and direction in the short term (b).




(a) (b)

Figure 13: Graph of VOC concentration in the pipeline area.

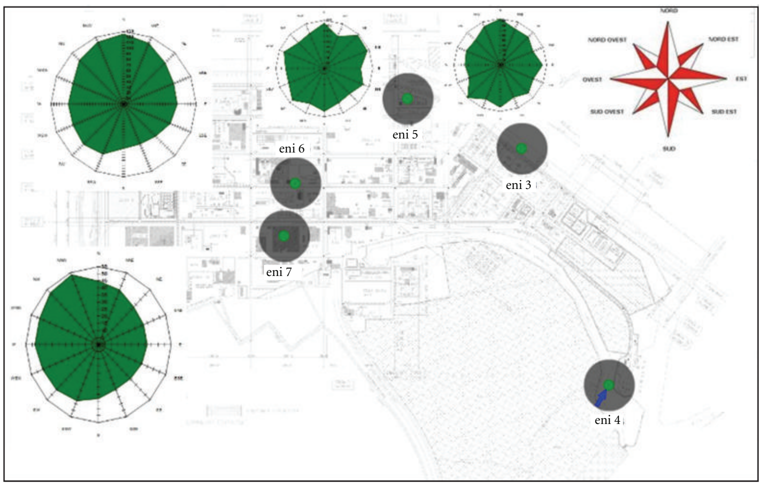
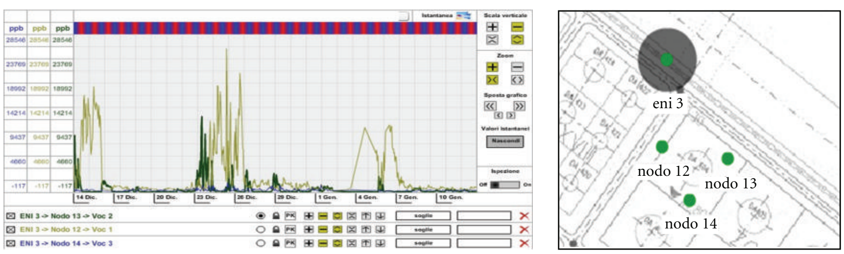



Figure 14: Example of data rendering—Correlation between wind and VOC concentration in four positions along the network.




(a) (b)

Figure 15: VOC concentration peaks detected in the benzene storage tank (floating roof).

low wind speed, conditions which favor the accumulation of pollutants from the nearby production plant. However, this was merely a local increase since the other sensors simultaneously recorded much smaller peaks. Furthermore, the values decreased from September on.

Figure 13 shows the trend of VOC concentrations in the pipeline area. Two sensors are positioned in the same area, but VOC 1 is closer to the emission sources and consequently has a higher background reading. Both sensors clearly demonstrate the cyclical effects of day and night.

When VOC sources need to be identified, the correlation between wind/speed direction and VOC concentration is vital; for this reason, a graphic representation relating these two parameters was mandatory. In Figure 14 different representations of VOC concentrations combined with the wind direction data are shown for four detectors located along the plant's perimeter; this particular plot shows the wind directions referenced to the north and the VOC concentration in ppb.

ENU 1, located in the southwest corner of the plant, is shown in Figure 14. VOC concentration is higher in quadrants I and IV, showing that the net VOC flow is entering the plant area. This may be related to the emissions generated by the traffic on the motorway running along the west side of the plant, or it may be due to emissions from other industrial sites, such as the petroleum refinery (WSW) and its storage area (WNW) located just across the motorway. In the same diagram, ENU 2, which is instead located at the northwest corner of the plant, the highest concentration values are in quadrants I and II; also in this case the VOC flow is coming from north of the plant area. In contrast, the other plots (near ENU 5) show a homogeneous distribution of VOC concentration from all directions. Hence, this format of data rendering allows PEM plant staff to quickly identify and visualize wind directions in areas of high levels of VOC concentration, while giving an overview of the predominant orientation of the VOC flux during the day.

The system's interface also allows users to keep tabs on specific areas, as in the case of the sensor network installed in the proximity of the benzene storage tank roof. In fact, data gathering was useful in identifying those phases in processing that are potentially more significant in terms of emissions. Specifically, concentration peaks are encountered with regular frequency (see Figure 15) after completely filling the tank; since, in such conditions, the floating roof is located closer to the sensors, eventual sealing problems along the perimeter of the roof due to wear or warping of the seals can be discovered. Furthermore, in the summertime the high volatility of the compounds could lead to variations in VOC concentrations during the emptying of the tank as well. Whatever the situation, the registered values, however, always are within the accepted range, since they are from a direct emissions source.

## 10. Conclusions

An end-to-end distributed monitoring system of integrated VOC detectors, capable of performing real-time analysis of gas concentration in hazardous sites at an unprecedented time/space scale, has been implemented and successfully tested at an industrial site near Mantova, Italy. The fundamental criteria for our system were providing the site with: a flexible and cost-effective monitoring tool that identifies emission sources in real-time year round, using easily redeployable and rationally-distributed monitoring stations that were suitable for all of the site's equipment, in order to achieve better management of abnormal situations.

Piloting the system allowed us to pinpoint additional key traits. For example, collecting data at 1-minute time intervals meets several needs: identifying short-term significant events, quantifying the emission readings as a function of weather conditions as well as of operational procedures, in addition to identifying potentially hazardous VOC sources in the plant area.

Moreover, the choice of a WSN communication platform gave excellent results, above all in allowing for redeploying and rescaling the network's configuration according to specific needs as they arise, while, at the same time, greatly reducing installation costs. Furthermore, real-time data through a web-based interface provided both adequate levels of control and quick data interpretation in order to manage specific situations. The program offers multiple formats for visualizing the data. In terms of the actual detectors, among the various alternatives available on the market, PID technology proved to meet all the major requirements, as PIDs are effective in terms of energy consumption, measuring range, cost, and maintenance once installed in the field. The energy budget was another significant element to be considered, particularly in ATEX Zone 0 areas, so secondary sources (PVPs) were adopted. Finally, fitting weather sensors at the nodes of the main network stations ensured a clearer understanding of on-field phenomena and their evolution, thus providing accurate identification of potential emission sources.

Future activity will involve, primarily, standardizing the application to allow deploying the WSN in other network industries (e.g., refineries), in addition to assessing WSN infrastructure monitoring of other environmental indicators.

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