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Sensing, Digital, and Management Strategies to Enhance the Built Environment Resilience in Cities

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Sensing, digital, and management strategies to enhance the built environment resilience in cities

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***Abstract*— Supporting the resilience of living environments is pivotal in a rapidly changing world, which has to co-exist with more and more frequent disruptive events. In order to cope with diverse hazards (e.g., earthquakes, landslides, blackouts, etc.), different technologies can contribute to develop a multidomain monitoring platform with a holistic perspective. Interoperability and modularity are fundamental to be able to regularly update and improve this tool according to the evolving needs of the whole ecosystem, considering living environments as well as citizens. This paper summarizes the innovative solutions developed by Università Politecnica delle Marche within the framework of the reCITY project, including sensing, digital, and urban planning technologies, hence providing a versatile smart monitoring platform able to support emergency management and decision-making processes.**

Keywords—digital platform, monitoring system, resilience, built environment, sensing technologies, digital technologies.

I. INTRODUCTION

Due to the increasing urbanization, it is essential to enhance the resilience (i.e., the capacity to withstand or recover quickly from difficulties) of the whole community with a view of social innovation [1]. This requires the consideration of the entire ecosystem, including citizens, buildings, and infrastructures. Economic, social, and institutional answers are needed to efficiently drive the change towards an intelligent, safe, and inclusive society [2].

Living environments should be modified in a perspective of becoming smart, sustainable, and capable to self-diagnose their own health status [3]. Initiatives such as Built4People [4] are meant to drive the innovation towards a people-centric, sustainable, and smart built environment. Several different tools and technologies can be exploited to these aims, including innovative materials, sensors, and digital tools as well as management procedures that pave the way for smoother strategies to face diverse types of hazards, being them natural (e.g., earthquakes, floods, and heatwaves) or energy-related (e.g., black-outs), just to cite some examples. Moreover, multifunctional materials able to respond to different requirements and to withstand several stimuli can make a step forward in the state of the art of the materials science and technology. In recent years, numerous studies dealing with sustainable, durable, and smart materials coupled to structural health monitoring (SHM) systems have been published. It is beyond doubts that continuously monitoring the status of a building can provide relevant information that can be processed in near real-time to eventually generate early warnings and support timely interventions [5]. Artificial Intelligence (AI) plays a key role in this context [6,7], since the forecasting of the variables of interest can empower to act in advance, thus anticipating potentially critical events and efficiently minimizing risks. On another hand, if it is true that AI can address complex challenges in smart cities, supporting resilience, sustainability, and technological advancement, other types of challenges should be considered as well, such as environmental costs, privacy related issues, cybersecurity social acceptance, (missing) regulatory frameworks, and transparency in AI usage [8].

The reCITY project [9] is well placed in this field, since it intends to create a human-centric social, economic, and technological system to valorise resilience practices that can support the community in case of emergency, adopting a collaborative framework capable to effectively put in place a holistic approach [10]. In particular, the objective is to activate an urban system that should be i) smart, able to provide personalized services, ii) sentient, capable to manage future scenarios thanks to data analytics techniques and innovative sensor networks, iii) social, empowering the citizens and making them active in the society. Within the framework of the reCITY project, the present authors covered multiple roles:

- To set sensor networks to regularly monitor structures and infrastructures, ensuring a timely detection of critical events mining the safety of people [11];
- To develop AI models to predict parameters of interest and generate early warnings, supporting decision-making processes especially in relation to critical structures/infrastructures and during emergencies (e.g., earthquakes and landslides) [12];
- To make urban districts more resilient from an energy point of view focusing on measures during critical events (e.g., blackouts, grid failures, etc.), affecting normal and emergency activities [13];
- To define how the urban planning tools can create earthquake-resistant communities combining zoning regulations, building standards, risk assessment, public awareness, and infrastructure resilience [14].

By adopting a holistic approach, these items contribute to reduce vulnerability, enhance community preparedness, and ultimately promote the community safety and well-being in seismic areas. To the best of the Authors' knowledge, at present no similar systems have been developed so far specifically for these hazards and exploiting the synergy between these technologies, materials, and tools to enhance the resilience of the built environment.

This paper aims to present the main achievements of these activities, underlining the impact on the resilience of living environments, paving the way towards a human-centric ecosystem promoting the community well-being.

II. IMPROVING BUILDINGS RESILIENCE

The Italian territory develops largely in an area of high seismicity. In the last fifteen years, many earthquakes have occurred especially in the central-meridional part of Italy [15], such as L'Aquila (Abruzzo) earthquake (2009), the Emilia Romagna earthquake (2012), the Amatrice-Norcia-Visso seismic sequence (2016-2017), and the Casamicciola Terme earthquake (2017). It is necessary to monitor multi-domain quantities to have a complete picture of the health status of a structure; the assessment of loads, vibrations, and related parameters is fundamental. In this project a multidomain modular and interoperable monitoring platform was developed including mainly sensors for electrical impedance, free corrosion potential, accelerations, ground water pressures, and ground displacements.

A. *A sustainable and durable self-sensing material*

The materials used to build living environments are fundamental for both the robustness and durability of a structure and the aspects related to its ability to perceive its own status. In the last thirty years, the so-called self-sensing materials field has skyrocketed, being able to sense variations of internal and external parameters (e.g., temperature or defects) [16]. They make it easier to develop monitoring strategies to promptly identify hazards and, hence, support risk mitigation. Within the framework of the reCITY project, also exploiting the results from the previous H2020 EU project EnDurCrete [17], cementitious materials were realized embedding sustainable conductive carbon-based additions (fillers and fibers). The self-sensing property was studied in terms of piezoresistivity, hence the ability to change electrical parameters with strain. Cement-based mortars and concretes were manufactured with recycled fillers and fibers, namely biochar (BCH) and recycled carbon fibers (RCF), whose synergistic effect was demonstrated both in terms of electrical conductivity, piezoresistivity, and durability.

B. *Sensing technologies to monitor buildings*

Multiple sensors were embedded in the cast self-sensing specimens, including electrical impedance sensors (in a 4-wire configuration, using an alternating current (AC) as excitation to avoid electrode-surface and material polarization, thus achieving more accurate results [18,19]) and free corrosion potential sensors. The former includes stainless-steel electrodes fixed in a 3-D printed case and connected to an acquisition board based on the AD5940 chip (Analog Devices, Wilmington, MA, United States); electrical impedance measurement is performed at 10 kHz, once per hour, according to Electrochemical Impedance Spectroscopy (EIS) method. The latter is a commercial pseudo-reference electrode (Cescor S.r.l., Italy) based on activated titanium with iridium-enriched mixed metal oxides (TiMMO) immersed in a cement mortar which keeps the pH constant around the electrode, ensuring its long-term stability. Each electrode is calibrated by the manufacturer and falls within the range between -70 and -50 mV/SCE. The electrode is fixed to the steel reinforcement embedded in the self-sensing cement-based material and connected to a data acquisition system developed ad hoc (Nplus S.r.l., Italy), which measures the free corrosion potential once per hour. It is extremely important to pay attention to possible interference between the two measurements; hence, sensing volumes should be thoroughly designed. Early warnings can be generated in case specific thresholds are overcome or values are far from the expected trend. In this case, a deeper inspection can be performed to detect the cause of the unexpected event. A distributed sensor network was realized, sending data (once per hour) to a unique hub allowing remote monitoring [20].

C. *Sensing technologies to monitor landslides*

Proper monitoring systems can enhance also the resilience of cities with respect to landslide hazard, protecting urbanized areas whose landslide physical model is known from previous long-term data. Critical parameters are related to climate (e.g., air temperature, humidity, and rains), groundwater regime (i.e., groundwater pressures, in the range of 10-1000 kPa), soil displacement, velocity, and acceleration. Typical sensors for geotechnical monitoring of landslides are piezometers, which are submersible measurement sensors designed to detect pore water pressures and ground water levels, such as foil-bonded or vibrating wire strain gauges. Sensors are differently arranged; their selection is conditioned by soil water conductivity and objective time response. Lateral movement underground is measured through MEMS digital in-place accelerometers. A distributed sensor network can give continuous information of lateral displacements along an instrumented vertical borehole in the ground. Typically, inclinometer systems can monitor horizontal displacements with a precision of 5 mm over a distance of 30 m. These signals analysis allows to understand the response of the landslide to environmental actions (e.g.,, earthquakes) and this can be used to implement an AI tool for forecasting time evolution of the specific phenomenon and minimize the risk for critical events [21]. Within the reCITY project, landslide risk has been studied with reference to the historical landslide of Ancona, a huge instability phenomenon (> 180 million m^3 of ground over a land of 2.2 x 0.5 km^2) that affects a critical corridor at the North entrance of the town, with an average rate of displacement of the order of 10^{-10} m/s [22]. The link between the evolution of the most critical mechanisms of the landslide, that is the sliding of a large volumes along preexisting rupture surfaces and the spatial/time distribution of the rains, clearly emerges from the analysis of monitoring data; thus, a limited number of sensors properly located can efficiently monitor the progress of instability processes. The Ancona Municipality has adopted an efficient monitoring system to control the landslide evolution together with an early warning system to protect the population. AI tools may be powerful to increase the efficiency of the system and the resilience of the town to critical events. A renewal of the monitoring system has been implemented with precise technologies suitable to measure the limited displacements of Ancona landslide (Fig. 1).

Inclinometers are mounted at fixed depths to detect deep displacements whereas piezometric cells (typically resistive or inductive) are used to monitor pore water pressures. The continuous monitoring of superficial displacements is ensured by satellite observations (INSAR) and by renewed topographical instruments scanning for displacements of existing manufacts and markers in the area. The monitoring platform can visualize ongoing processes and compare values with prescribed limits for early warning generation.

D. *A long-term AI-enabled monitoring system*

The digital monitoring platform was based on the FIWARE ecosystem [23], integrated also with a platform (Dashram) developed by Engineering SpA. Different components and services were integrated for the analysis of time series data measured by diverse sensors, managed through CrateDB, and processed also using Jupyther notebooks with Python and R runtimes (Fig. 2).

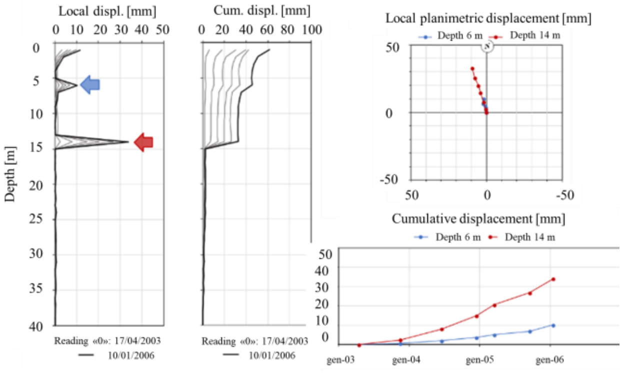


Fig. 1. Patterns of horizontal displacements at the Ancona landslides. Peaks indicate the passage of the rupture surfaces in the ground.

Forecasting is one of the most important services; future values are forecasted from time-series data using state-of-the-art approaches (e.g., Prophet for fast and reliable seasonal forecasts and Neural Prophet, combining traditional time-series forecasting with the power of neural networks for improved accuracy). Prophet is a forecasting tool that breaks down a time series into its additive components, using a piecewise linear or logistic growth curve for trend analysis. Seasonal patterns are identified through Fourier series expansion, which allows for the modelling of abrupt changes.

The forecasts of electrical impedance values are then compared against a pre-defined acceptable threshold. If the values deviate from this range, an alert system is triggered. This early warning system enhances the ability to respond promptly and proactively mitigate potential damages. The training of the model involved both selection and hyperparameter tuning, facilitated by cross-validation to optimize forecasting accuracy. The training was carried out on a dataset of thousands of electrical impedance signals split into 90% for training and 10% for testing, with part of the training set further set aside as a validation set to fine-tune the model without overfitting. The forecasting was conducted on 10% of the time series data, and its performance was assessed using the following metrics: Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), Root Mean Square Error (RMSE), and correlation. The obtained results show average values of 0.5 Ω for both MAE and RMSE, an average MAPE of 0.1%, and a correlation of 95%.

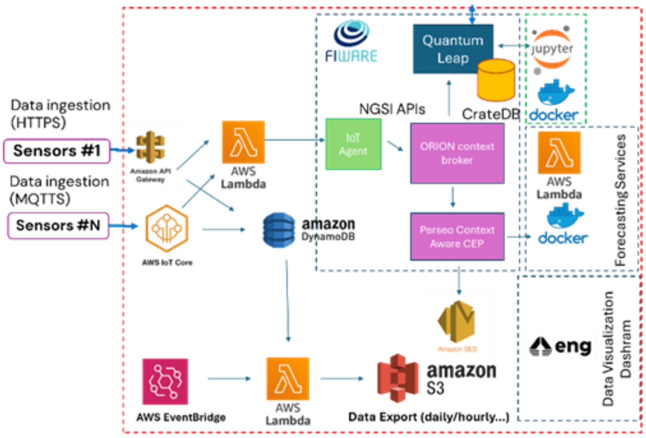


Fig. 2. Architecture based on FIWARE and cloud services to manage data ingestion, processing and visualization.

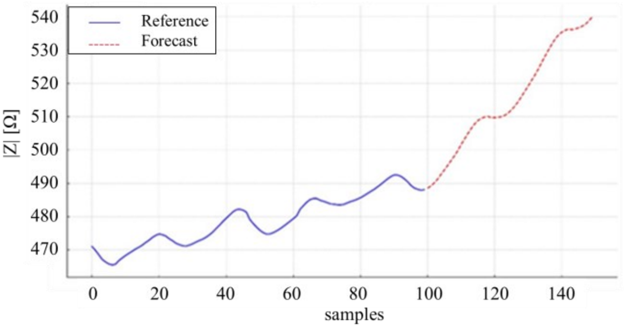


Fig. 3. Example of forecasting of electrical impedance module.

Leveraging the serverless architecture, the service automatically scales computing resources to handle data processing and model training.

An example using NeuralProphet starting from data collected on self-sensing materials [12,24] is reported (Fig. 3). A user-friendly interface allows users to receive forecasts, visualize future trends, and obtain insights through advanced time-series analysis. An example of data visualization is shown (Fig. 4).

III. ENERGETIC RESILIENCE

From an energy point of view, the concept of resilience concerns the electric/natural gas grid, which can be affected by several issues. Blackouts (electric grid) or electric/natural gas grid failures can lead to severe problems for the normal and emergency activities of people [25]. Energy conversion technologies installed close to the consumers, and directly connected to them, are the best options to continue the provision of electricity/natural gas to energy-intensive services (e.g., hospitals, civil protection, etc.) [26]. The prompt operation of these technologies when issues occur is fundamental to avoid a shortage of electricity/heat; thus, the correct management of possible failures is pivotal for having a continuous provision of the service [27]. In this regard, the main activities related to the increase of the electric/natural grid resilience from severe issues in the framework of the reCITY project included i) the development of a monitoring platform capable of alerting of possible failures, helping in identifying and locating the fault to find a solution, and ii) the development of (mostly) multi-carrier based Local Energy Communities (LECs) to produce and consume energy locally without relying on national grids. This represents a form of resilient energy self-sufficiency (highly promoted by the European Community) able to lower the energy poverty levels of places that cannot be easily connected with the national electric/natural gas grid.

A. Overview of the current energy situation of the UNIVPM campus (Montedago site)

Within the reCITY project, a monitoring platform of the end-users within the overall UNIVPM campus in the city of Ancona (Italy) was developed. The end-users are indeed located in different zones of Ancona: i) Monte Dago site (with the Faculties of Agriculture, Engineering, and Environmental Sciences); ii) the Faculty of Economics (Ancona city centre); iii) the Faculty of Medicine and the city hospital (Torrette, Ancona, far from the city centre); iv) the university administration (city centre); v) the university sport centre (close to the Faculty of Medicine). The platform regularly provides data on energy consumption, temperature, and air quality of these facilities (Fig. 5). Moreover, the energy production of some energy conversion technologies installed within the UNIVPM campus in the Monte Dago site (e.g., a Combined Heat, and Power – CHP – unit and natural gas boilers) and the Faculty of Medicine (e.g., another CHP unit) are monitored as well. These two technologies provide heat to the buildings located in the Monte Dago site, while another CHP provides heat to the buildings of the Faculty of Medicine and the city hospital. It is worth noting that all the zones previously mentioned have a gen set each to provide electricity for a short period (e.g., hours) to the facilities located in each zone. However, the Monte Dago site has been considered the most interesting zone, being a multi-carrier LEC with locally produced and consumed energy. Further studies regarding the installation of renewables (e.g., photovoltaics) and energy storage systems (e.g., electric batteries or hydrogen-based integrated systems) is of interest to increase the resilience of the site as well as of other possible LECs still to be deployed.

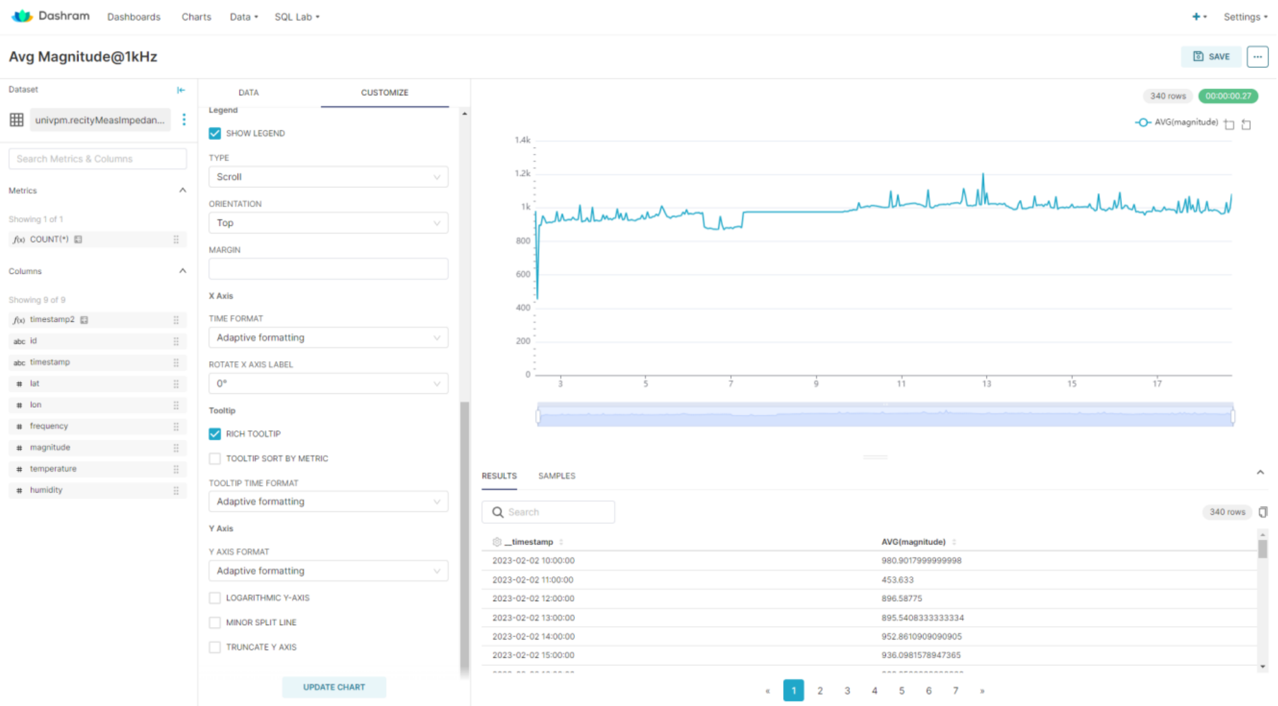
IV. COMMUNITY RESILIENCE

Monitoring tools, infrastructure, and community preparedness are crucial for seismic events responsiveness. The urban-territorial study conducted as part of the reCITY project focused on the Central Italy area, severely affected by the earthquake in 2016 (reaching a magnitude of 6.5 Mw). This study covered four regions, ten provinces, and 139 municipalities (approximately 8000 km^2). Among the four regions within the seismic "crater" area, the most severely affected was the Marche Region, with an impressive impact: > 104000 damaged buildings, 54000 evacuated structures, and 32000 displaced individuals.

Sixteen municipalities have >30% of the population living in temporary housing solutions; 9 severely affected municipalities have >50% of the population displaced of home [28]. The analysis of urban responses in the investigated case studies has underscored crucial factors shaping resilience strategies: community involvement, flexibility, and resource management. Preparing a community for seismic hazards requires a comprehensive and collaborative approach integrating education, planning, infrastructure improvements, and community engagement. Key steps were identified:

- Raise awareness and educate residents about seismic hazards and threats as well as promote preparedness, including guidance on assembling emergency kits, developing family emergency plans, and understanding evacuation procedures.
- Community training and drills and early warning systems, providing timely alerts (e.g., sirens, text alerts, or smartphone apps) before seismic events; ensure proper training on alerts.
- Emergency response planning including evacuation routes, designated emergency shelters, and communication strategies; foster collaboration and coordination with local emergency services.
- Community engagement in planning and decision-making process, encouraging active participation in community emergency response teams; foster a sense of community responsibility and mutual aid [29].
- Inclusive planning, considering the needs of vulnerable population (e.g., elderly, individuals with disabilities, and those with limited resources).
- Green spaces and safe zones serving as seismic buffers for community gatherings during/after earthquakes; designate open spaces that can serve as assembly points and temporary shelters [30].
- Continuous monitoring and adaptation to monitor seismic activity, providing real-time information to residents; regularly assess and update community preparedness plans [31].

Public communication strategies to disseminate information before, during, and after earthquakes, ensuring timely updates and instructions to stay safe.



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2023-02-02 11:00:00	453.633
2023-02-02 12:00:00	896.58775
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2023-02-02 14:00:00	952.8610909090905
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Fig. 4. Example of electrical impedance signal (1 kHz) of self-sensing materials visualised the Dashram platform.

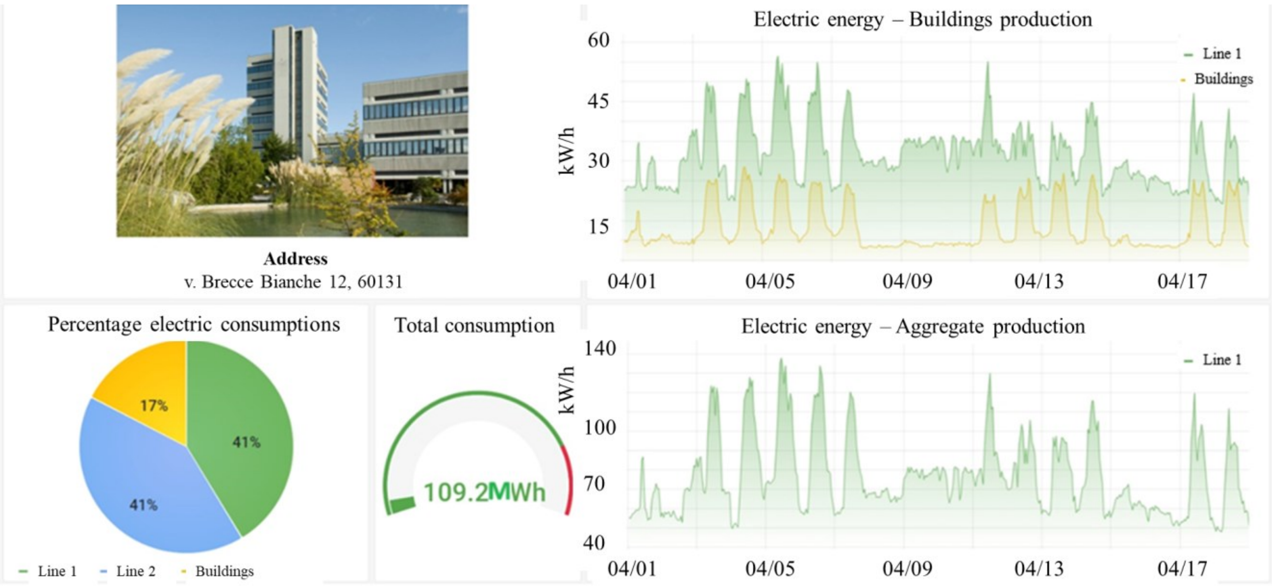

Fig. 5. Dashboard of the monitoring platform showing the electricity consumption, showing location (top, left), consumptions (bottom, left), and energy production (right).

V. DISCUSSION AND CONCLUSIONS

The activities performed by UNIVPM within the framework of the reCITY project led to modular, scalable, interoperable, multidomain solutions enhancing the resilience of the built environment towards different hazards. Different scales were considered, from territory to buildings and infrastructures, through community and electricity networks. The main outcomes include an AI-enabled monitoring platform capable of timely detect potential issues on a building and supporting interventions during emergencies. Both structural and energetic aspects are monitored, fostering timely interventions thanks to early warnings generation. Moreover, the community preparedness to efficiently react in case of emergencies has been promoted through the definition of strategic resilience-enabling guidelines. This contributes to enhance the resilience of the built environment, also favoring the well-being of citizens and paving the way to a human-centric and co-participating planning of the whole ecosystem. Future research and developments on this topic should focus on the integration of the proposed material and sensing solutions to existing buildings, also having their own pre-existent monitoring and management systems that should be integrated. For these reasons, modularity and interoperability are fundamental design criteria. Moreover, the integration of the measurement results with BIM models could also be relevant towards digital transition of the built environment as well as for more efficient management and maintenance operations of the building.

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