A Distributed IoT Software Infrastructure for Multi-Purpose Services in Multi-Energy Systems

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1st Rafael Natalio Fontana Crespo
Politecnico di Torino
Turin, Italy
Email: rafael.fontana@polito.it

2nd Yingjun Luo
Politecnico di Torino
Turin, Italy
Email: yingjun.luo@studenti.polito.it

3rd Manuela Baracani
Politecnico di Torino
Turin, Italy
Email: manuela.baracani@polito.it

4th Paolo Squillari
Politecnico di Torino
Turin, Italy
Email: paolo.squillari@polito.it

5th Fabio Favoino
Politecnico di Torino
Turin, Italy
Email: fabio.favoino@polito.it

6th Edoardo Patti
Politecnico di Torino
Turin, Italy
Email: edoardo.patti

***Abstract*—The Internet of Things (IoT) is fundamental in advancing towards Multi-Energy Systems. Ubiquitous devices have the potential to generate considerable data that can enable, for example, real-time monitoring of countless applications. The requirements and context of different services and applications, such as renewable power generation and smart building monitoring, may differ considerably in a cross-context scenario like Multi-Energy Systems. Nonetheless, collecting and managing this heterogeneous cross-context data can unlock the development of new analytics that can link this information and provide valuable insights for decision-making processes. However, the collection, storage and management of the vast amount of heterogeneous data generated in this variety of applications poses a significant challenge in developing a unique IoT software infrastructure that ensures interoperability and reliability among the different devices and services. This paper presents a vendor-agnostic multi-purpose platform to collect, store, manage and analyse heterogeneous data in Multi-Energy systems. Furthermore, the platform enables the management of heterogeneous devices that implement different communication protocols. To test the proposed platform, we showcase its implementation in two use cases with different requirements due to their diverse contexts. On one hand, the monitoring of Indoor Enviromental Quality (IEQ), a critical parameter that asses the internal comfort of buildings. On the other hand, the real-time monitoring and forecasting of the wave power delivered to the grid of the Inertial Sea Wave Energy Converter- the ISWEC, a device that converts waves motion into electrical power through the inertial effect of a gyroscope.**

***Index Terms*—Multi-Energy Systems, Multi-Purpose Platform, IEQ, IoT Platform, WEC, Energy Forecast**

I. Introduction

The rapid advancements in technology have led to a paradigm shift in cities, prompting a determined effort to address their challenges related to sustainability and population quality of life, leading to the transformation of these urban areas into smart cities [1]. Smart cities represent a transformative approach to urbanisation, leveraging cutting-edge technology to optimise resource utilisation, enhance the quality of life, and foster economic prosperity [2]. In this context, developing Multi-Energy Systems (MES) is crucial to the transition towards sustainability. MES involve the optimal interaction of various energy sources such as electricity, heat, cooling, fuels, and transportation, operating in synergy across different scales, including district, city, or national levels [3].

Information and Communication Technology (ICT) and the Internet of Things (IoT) are not just two key technology enablers but the backbone that plays a crucial role in developing and operating MES [4]. These technologies are the foundation for efficiently collecting, storing and analysing vast amounts of data, making them indispensable in the Multi-Energy systems scenario. However, in a MES scenario, data come from various sources, including sensors, devices and systems. The heterogeneity of data formats and communication protocols, among other factors, pose significant challenges in developing software infrastructures that ensure interoperability and reliability for cross-domain context applications like the ones involved in Multi-Energy Systems such as electricity networks and heat/cooling systems.

Existing literature offers a wealth of studies proposing frameworks and architectures for managing heterogeneous data from Multi-Energy systems. However, these solutions often have a narrow and vertical approach, addressing and focusing only on specific applications of MES such as transportation [5]–[7], smart grid management [8]–[10], renewable energy sources [11]–[13] and smart buildings [14]–[16]. For example, in [12], an architecture was proposed for monitoring and detecting failures of a Wave Energy Converter, a device used to convert the power coming from the waves into electrical energy. Wave Energy Converters (WECs) are a promising technology for harnessing ocean energy that will reduce the utilisation of fossil fuels. In the case under study, the proposed infrastructure was implemented to collect data from a floating pendulum Wave Energy Converter. These data were employed to implement data-driven condition monitoring and fault detection for the hydraulic system of the WEC. Nonetheless, the infrastructure relied on proprietary license

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software, Thingspeak [17], a MathWorks IoT platform that stores, post-processes and retrieves data. Moreover, as was previously stated, it only focused on a particular application, the wave power energy source.

In this work, we propose a vendor-agnostic multi-purpose platform that provides a unified framework able to collect, store, and manage heterogeneous data coming from cross-context applications in a Multi-Energy Systems scenario. The platform, based on the microservices-design pattern, supports both synchronous and asynchronous communication, and its functionalities can be easily extended in a plug-and-play fashion. To illustrate the potential of the proposed platform, we test its implementation in two compelling use cases: Indoor Environmental Quality (IEQ) and Inertial Sea Wave Energy Converter (ISWEC) case. IEQ encompasses the assessment of thermal comfort, indoor air quality, illumination, and acoustic parameters within enclosed environments [15]. Since people spend approximately 90% of their total lifetime indoors, IEQ is a critical parameter that impacts both human health and social well-being [14]. We present the platform implementation for IEQ monitoring and the integration of a plugin for assessing thermal comfort. On the other hand, we showcase the implementation of the platform for monitoring the power generated by the Inertial Sea Wave Energy Converter (ISWEC) [18], a WEC that harvests the power from the wave's motion through the inertial effects of a gyroscope. Moreover, the platform integrates a module for forecasting the power delivered to the grid of the ISWEC. The monitoring and forecasting of the power delivered to the grid of the ISWEC unlocks a significant step towards sustainability, facilitating the replacement of fossil fuels with Renewable Energy Sources.

This work is structured as follows. Section II introduces the proposed Multi-Purpose infrastructure. Section III showcases the platform implementation for monitoring and forecasting the power delivered to the grid of the ISWEC device. Section IV outlines the implementation of the platform for IEQ monitoring. Moreover, the platform integrates a module for post-processing the raw data collected and asses IEQ from the point of view of thermal comfort. Section V presents communication tests performed on the platform and the experimental results obtained. Furthermore, it presents the *IEQ Thermal Comfort* and the *ISWEC Power Forecasting* results. Finally, Section VI presents the closing remarks.

II. Platform Description

In this section, we introduce the proposed Multi-Purpose Platform. We strive to design a microservices-based platform that ensures: i) *reliability*; ii) *scalability*; iii) *modularity*; iv) *flexibility*; v) *extendibility*; vi) *interoperability*; vii) *standardisation*; viii) *decentralisation*; ix) *security*; x) *asynchronous communication*; and xi) *synchronous communication*. Moreover, the platform must integrate appropriate technologies to handle heterogeneous devices and data formats.

For this purpose, we developed the Multi-Purpose platform, depicted in Fig. 1. The platform follows the microservices design pattern and provides Representational State Transfer (REST) Application Programming Interfaces (APIs) for internal and external communications. It integrates different state-of-the-art relational (*PostgreSQL*), time-series (*InfluxDB*), and document-oriented (*MongoDB*) databases in order to employ

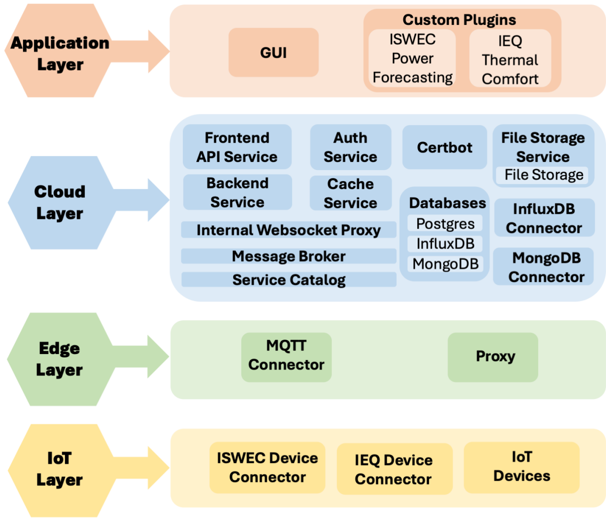

Fig. 1. Proposed Multi-Purpose Platform architecture

the most appropriate technology according to the data type that has to be managed. Moreover, the platform design facilitates the seamless integration of new functionalities (e.g. *ISWEC Power Forecasting* and *IEQ Thermal Comfort*) in a plug-and-play fashion. These functionalities can interact with the other platform components using REST or the Message Queuing Telemetry Transfer (MQTT) protocol, thus supporting both Request/Response and Publish/Subscribe communication paradigms.

As illustrated in Fig. 1, the platform is a fourth-layered architecture, with i) *IoT Layer*, ii) *Edge Layer*, iii) *Cloud Layer*, and iv) *Application Layer*. The lower layer in Fig. 1, the *IoT layer*, includes the devices in the field that can be IoT enabled (*IoT devices*) or connected to the Internet through *Device Connectors*, like the *ISWEC Device Connector* or the *IEQ Device Connector*.

The *Edge Layer* comprises the *MQTT Connector* and the *Proxy*, supporting both the Publish/Subscribe and the Request/Response communication paradigms. The *MQTT connector* handles asynchronous (MQTT) communication between the devices in the field and the platform, while the *Proxy* manages synchronous (REST) communication.

The third layer, the *Cloud layer*, is the platform's core and integrates several components with distinct functionalities. The *Message Broker* manages asynchronous (MQTT) communication among the platform components. On the other hand, the *Internal Web Socket Proxy* handles synchronous (REST) communication between the platform components and distributes the workload between them. The *Auth Service* governs user and device authentication, implementing JsonWebTokens (JWT), a modern security approach. Additionally, *Certbot* automates certificate generation to ensure secure external connections. These certificates allow the utilisation of the Hypertext Transfer Protocol Secure (HTTPS). The *Frontend API Service* executes initial verifications, dispatching requests to the *Internal Web Socket Proxy* and retrieving asynchronous responses from it. The *Service Catalog* is a service registry system. Additionally, it keeps track of the status of the different platform services. The *Service Catalog* serves as the primary access point for applications and other components, enabling the discovery of the available services and endpoints within the platform.

The platform integrates diverse *database* technologies to store various data types using the most suitable technology, as illustrated in Fig. 2: *PostgreSQL*, *Cache Service*, *InfluxDB*, *MongoDB* and *File Storage Service*. *PostgreSQL* is a relational database that stores non-time-series related data (e.g. metadata of users and use cases). The *Cache Service* provides access to recently stored time-series data. The *Backend Service* handles the data transmission to and from *PostgreSQL* and the *Cache Service*. It communicates with the *Internal Websocket Proxy* using REST. *MongoDB* is a non-relational database that stores non-relational data, such as the *device* and *service catalog* data. We integrate *MongoDB* due to its data structure flexibility and better performance than relational databases for creating, updating, reading and deleting operations in the Big Data scenario [19]. The *MongoDB Connector* manages *MongoDB* data and enables data exchange using REST APIs. *InfluxDB* is a time-series database that stores telemetry data (e.g. ISWEC power and IEQ measurements) with its corresponding timestamp. The platform integrates the *InfluxDB Connector* to manage *InfluxDB* persisted data. This microservice exposes REST APIs to exchange time-series telemetry data and store this information in *InfluxDB*. Furthermore, the platform comprises *File Storage* to save file data types. The *File Storage Service* is the microservice responsible for file management. It exposes REST APIs for transmitting, retrieving and deleting files within the *File Storage*. Moreover, it exposes a REST API for fetching a *zip* file. Given potential large-size files, the microservice performs file compression ”on-the-fly” to guarantee good performance in terms of time, memory and user experience.

The highest layer in the proposed platform is the *Application Layer*, as depicted in Fig. 1. This layer supplies tools to empower users with the possibility to develop distributed applications and services to manage and retrieve data deriving from the underlying layers. In this way, the needs of the different stakeholders can be addressed. These applications can be disseminated across the internet and employ either MQTT or REST protocols to exchange information with the platform. Additionally, the platform facilitates the expansion of its capabilities in a plug-and-play manner through the seamless integration of lightweight applications, referred to as *Custom Plugins*. These *Custom Plugins* are subscribed to the *Message Broker*, consuming messages and executing their tasks. Two developed plugins will be presented afterwards: the *ISWEC Power Forecasting* (described in Section III) and the *IEQ Thermal Comfort* (presented in Section IV) modules.

III. Use Case: ISWEC Grid Power Monitoring and Forecasting

Renewable Energy Sources are an auspicious form of energy for reducing the usage of fossil fuels as energy sources. The usage of renewables has increased significantly in the last few years. In this context, Wave Energy has arisen as one of the most promising sources in the renewables field due to its great potential [20]. A Wave Energy Converter is required to capture the power coming from the waves and transform it into electrical power. The Inertial Sea Wave Energy Converter (ISWEC) [18] is a device that transforms the power coming from the waves into electrical power employing the inertial effects of a gyroscope.

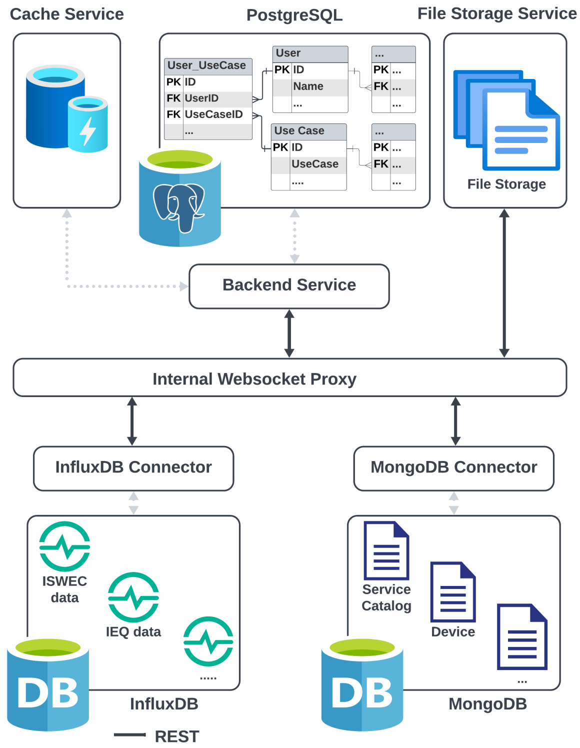

Fig. 2. Platform data storage schema

As occurs for other renewable sources (e.g. wind and solar), the electrical power generated from the ISWEC fluctuates because of waves’ sporadic and unpredictable characteristics [21]. These fluctuations make the integration of the ISWEC into the electric power grid a challenging task. Recent works state that these challenges can be overcome by forecasting the power delivered to the grid of the ISWEC [22].

We implemented the proposed multi-purpose platform to monitor and forecast the power delivered to the grid of the ISWEC device. We emulated the *ISWEC Device Connector* that collects these power measurements. The power is sampled every 0.1s [22]. However, the *ISWEC Device Connector* collects ten measurements and sends these data every 1s to the platform through the MQTT protocol working as a publisher. These data are received by the *InfluxDB Connector* (MQTT subscriber) and then stored in *InfluxDB*.

Furthermore, the platform integrates the *ISWEC Power Forecasting* module. This module is a custom plugin that, based on a Long Short-Term Memory Neural Network (LSTM), forecasts the power delivered to the grid of the ISWEC device in a 1min horizon [22]. The 0.1s power measurements are retrieved from the *InfluxDB Connector* using HTTP communication and temporarily aggregated in time steps of 30s using a simple sliding, non-overlapping moving average window technique. We implemented an LSTM architecture consisting of two hidden layers, with 128 LSTM units in the first layer and 64 LSTM units in the second layer. Moreover, the algorithm employs eight regressors (i.e. time lag) and a batch size equal to eight, as done in [22]. Nevertheless, we employed a more robust dataset consisting of 48h for training the model. Since the original dataset was downsampled in time steps of 30s, the training dataset consisted of 5760 (versus 2700 employed in [22]).

The *ISWEC Power Forecasting* module provides REST

APIs for launching and stopping the predictions. Furthermore, the module provides REST APIs for retrieving the forecast results.

IV. Use Case: Indoor Environmental Quality Monitoring and Post-Processing

Multiple studies indicate that residential and commercial buildings contribute approximately 30%–40% of the total energy usage in Europe and the United States [23], [24]. Among these, HVAC systems (heating, ventilation, and air conditioning) account for more than 50% of a building's total energy consumption [25]. In this context, Indoor Environmental Quality (IEQ) can be crucial in optimising buildings' energy consumption while keeping users comfortable. IEQ encompasses thermal comfort, indoor air quality, lighting, and acoustics in indoor environments. Enhancing IEQ can result in more efficient energy utilisation in buildings while ensuring occupants' comfort.

We implemented the proposed platform for monitoring IEQ in a real-world scenario. We monitored different IEQ variables, such as room air temperature, mean radiant temperature, room global illuminance, air velocity, $C0_2$ level, and relative humidity. These variables are sampled every 5min using the corresponding sensor technology for each case and sent to the *IEQ Device Connector* using the ModBus protocol. Afterwards, the *IEQ Device Connector* sends these data to the platform through the MQTT protocol (MQTT publisher). The *InfluxDB Connector* receives these data and saves it in the *InfluxDB*. The *IEQ Device Connector* hardware is built on top of an R-Pass device.

Moreover, the platform includes the *IEQ Thermal Comfort* module. This module is a custom plugin that aims to assess the IEQ from the point of view of thermal comfort. The plugin computes the Operative Temperature (T_{op}) to calculate the perceived human thermal comfort. T_{op} is a simple measure derived from air temperature (T_a), mean radiant temperature (T_r), and air velocity (V_a). It is computed as follows:

$$T_{op} = \frac{T_a \cdot \sqrt{10 \cdot V_a} + T_r}{1 + \sqrt{10 \cdot V_a}} \tag{1}$$

In order to compute the ideal temperature range for the building's occupants, we calculate the Optimal Operative Temperature (T_{oop}). The calculation of the T_{oop} depends on the analysed environment. For the case of buildings that are used as offices or occupied mainly by people with sedentary activities, where there is no active air-conditioning, and it is simple to open/close the windows, the T_{oop} is computed based on the Outdoor Running Mean Temperature (T_{rm}):

$$T_{rm} = \frac{T_{t-1} + 0.8T_{t-2} + 0.6T_{t-3} + 0.5T_{t-4} + 0.4T_{t-5} + 0.3T_{t-6} + 0.2T_{t-7}}{3.8} \tag{2}$$

$$T_{oop} = 18.8 + 0.33T_{rm} \tag{3}$$

where T_{t-n} is the average temperature of the n preceding days (in $^{\circ}C$).

The T_{oop} is the temperature preferred by more than 95% of the people. Nonetheless, there exist different categories and tolerances: *Category I*, with a tolerance of ±2, has a 94% of acceptance; *Category II*, with a tolerance of ±3, has a 90% of acceptance; and *Category III*, with a tolerance of ±4, has an 85% of acceptance.

V. Tests and Results

This section presents tests conducted on the platform implementation for both use cases previously presented in Sections III and IV. First, we will present communication tests that have been performed to assess the transmission performance of the different platform entities for sending and retrieving data over the Internet. Moreover, we will showcase the forecasting results obtained with the *ISWEC Power Forecasting Module*. Last but not least, we will present the *IEQ Thermal Comfort* results for a room monitored for almost one month.

A. Communication and Computation performance

To evaluate the transmission performance of the proposed platform, we performed communication tests to assess the time required by various system services to transmit and receive data using the MQTT protocol. The *ISWEC Device Connector* and the *IEQ Device Connector* are MQTT publishers, while the *InfluxDB Connector* works as an MQTT subscriber. We will refer to these entities as publishers and subscribers, depending on their role. We perform the tests in a Local Area Network (LAN) and a Wide Area Network (WAN). In the first case, publishers, *Message Broker*, and subscribers are in the same location. On the contrary, in the WAN case, these actors are situated in different locations and communicating over the Internet.

In the ISWEC Power monitoring case, data payloads of 909 bytes were transmitted every 1s during the tests. Fig. 3 (b) depicts the box plots with the distribution of the transmission latencies when monitoring the power delivered to the grid of the ISWEC, both in LAN and WAN. This latency corresponds to the *round-trip time*, representing the time elapsed between the packet sent by the publisher (*ISWEC Device Connector*) and received by the subscriber (*InfluxDB Connector*). The graphs also include in red the outliers, i.e. values exceeding one and a half times the length of the box on both ends [26]. The median transmission latency in the LAN case equals 0.022s, while in the WAN, it is 0.045s. Furthermore, the first and third quartiles (reported as Q_1 and Q_3 in Fig. 3 (b)) for the LAN case equal 0.020s and 0.025s, respectively. Instead, Q_1 and Q_3 are 0.043s and 0.046s for the WAN case. The lower and upper whiskers, denoted as W_1 and W_2 in Fig. 3 (b), span from 0.013s and 0.032s in the LAN case and from 0.039s and 0.050s in the WAN case. Therefore, in the LAN case, nearly 97% of the packages are transmitted in less than 0.032s, while in the WAN case, it is 0.050s. As expected, the transmission time of the LAN case is lower than that of the WAN case.

In line with the preceding analysis, tests were conducted to assess the computation time of the *ISWEC Power Forecasting* module. Fig. 3 (c) reports the computation times of the *ISWEC Power Forecasting* module for both cases (LAN and WAN). This computation time encompasses: i) retrieving the last 4min measurements (2400 data points) from the *InfluxDB Connector* using HTTP; ii) downsampling the data in 30s time steps; and iii) computing the predictions through the LSTM model for the next minute. The median value obtained for the LAN case is 1.653s, while for the WAN case is 2.169s. Furthermore, the top whiskers are 1.834s and 2.444s, respectively.

In correspondence with the performance classifications defined by the *IEC-61850* standard [27] (refer to Table I),

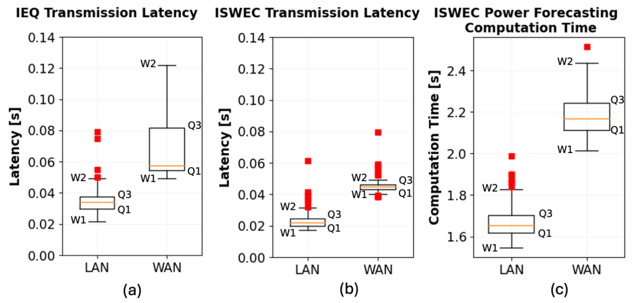

Fig. 3. Experimental results obtained for (a) IEQ Monitoring transmission latency; (b) ISWEC Power Monitoring transmission latency; and (c) ISWEC Power Forecasting computation time

TABLE I
COMMUNICATION REQUIREMENTS AND PERFORMANCE CLASSES FOR POWER SYSTEMS DEFINED BY IEC-61850 [27]

Performance Requirements	Performance Classes	Values	Examples of Services
	TT0	>1000 ms	Files, events, log contents, SCADA
	TT1	1000 ms	Events, alarms
	TT2	500 ms	Operator commands
Transfer Time	TT3	100 ms	Slow automation interactions
	TT4	20 ms	Fast automation interactions
	TT5	10 ms	Releases, status changes
	TT6	3 ms	Trips, blockings

the transmission latencies obtained both in LAN and WAN cases when monitoring the ISWEC power (illustrated in Fig. 3 (b)) demonstrate that the infrastructure for this scenario is compliant with classes *TT0*, *TT1*, *TT2* and *TT3*. When considering both the transmission latency of the ISWEC monitoring (Fig. 3 (b)) and the computation time of the *ISWEC Power Forecasting* module (Fig. 3 (c)), the overall durations are less than 2.1s and 2.6s for LAN and WAN. These results align with the *TT0* performance class, which is still compliant with the type of application since the ISWEC power monitoring and forecasting can be comprised in the SCADA category. Additionally, the ISWEC use case results show that the infrastructure can accomplish real-time forecasting if we consider that these predictions are performed every 30s with a forecasting horizon of one minute.

In the IEQ case, the tests were carried out only to calculate the transmission latency from the *IEQ Device Connector* (MQTT publisher) to the *InfluxDB Connector* (MQTT subscriber). The *IEQ Thermal Comfort* computation time was not analysed since it is not a real-time sensitive application: the user can launch the analysis when preferred and analyse variable amounts of data (from hours to days) depending on its' interest. For IEQ monitoring, the tests were performed by transmitting data payloads of 9275 bytes every 5min. The box plot distribution of the transmission latency of 100 packets sent in LAN and WAN is illustrated in Fig. 3 (a). In the LAN scenario, the median transmission latency is 0.034s, while in the WAN case, it is 0.058s. Additionally, Q_1 and Q_3 for the LAN case are 0.030s and 0.038s, respectively. For the WAN scenario, the first and third quartiles are 0.054s and 0.082s. W_1 and W_2 range between 0.018s and 0.049s in the LAN case and from 0.013s and 0.123s in the WAN scenario. When comparing the top whiskers (W_2) of the WAN and LAN case in both the IEQ and ISWEC scenarios, it can be seen that the

TABLE II
ISWEC POWER FORECASTING RESULTS IN TERMS OF MAD [%], RMSD [%] AND R^2

Metric	Prediction Horizon [s]	
	30	60
MAD	10.72	14.39
RMSD	14.48	19.02
R^2	0.85	0.75

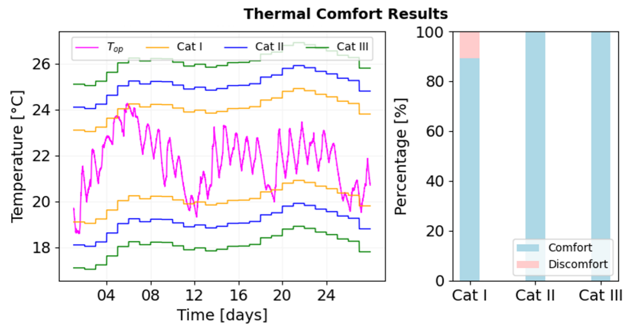

Fig. 4. IEQ Thermal Comfort results

transmission latency difference is more notorious in the IEQ case (0.074s) than in the ISWEC (0.018s). This difference can be due to the considerable difference in the packet size: 9275 bytes in the IEQ case versus 909 bytes in the ISWEC.

B. ISWEC Power Forecasting Results

To assess the model accuracy we employed three metrics: i) *Coefficient of Determination* (R^2), ii) *Mean Absolute Difference* (MAD), and iii) *Root Mean Squared Deviation* (RMSD) (refer to [22] for more details).

We monitored and predicted the power delivered to the grid of the ISWEC device for a dataset consisting of 12h, which is distinct from the one used for training. Moreover, this dataset is different too from the one employed in [22]. The original data sampled every 0.1s were downsampled in time steps of 30s, totalling 1440 data points. The forecast results are reported in Table II. The accuracy of the models dropped as the horizon increased. Despite employing a more robust dataset for training than in [22] (48 hours versus 22.5 hours), the results in terms of MAD and RMSD are similar. However, there is a notable improvement in terms of R^2: for one and two steps ahead (i.e. 30s and 60s), the results are 0.85 and 0.75, respectively, versus 0.79 and 0.66 obtained in [22].

C. Thermal Comfort Results

We monitored and analysed the thermal comfort of a room for 27 days. The left side of Fig. 4 reports the results for the T_{op} and the different ranges for each T_{oop} category reported in Section IV. As shown, the T_{op} is within the range established by *Category II* (and thus *Category III*) for all the evaluated periods (100% of the time). The right part of Fig. 4 shows the bar graph representing the percentage of comfort/discomfort according to the three categories. The T_{op} was in the comfort zone of *Category I* for 90% of the time.

VI. CONCLUSIONS

In this work, we presented a distributed software platform based on microservices that is able to collect, store, and manage heterogeneous data coming from cross-context applications in a multi-energy system scenario. The platform architecture integrates different database technologies to store heterogeneous data efficiently. Furthermore, the platform design facilitates the seamless integration of new functionalities in a plug-and-play fashion.

Moreover, we test the platform implementation for two different applications, namely Indoor Environmental Quality and the monitoring and forecasting of the power generated by the ISWEC, demonstrating the platform flexibility, interoperability and reliability for managing completely different context applications. Integrating such cross-context applications unlocks the potential of developing new analytics to find possible relations between these data and provide valuable insights.

REFERENCES

[1] J. Pereira *et al.*, "A platform for integrating heterogeneous data and developing smart city applications," *Future Generation Computer Systems*, vol. 128, pp. 552–566, 2022.

[2] E. Al Nuaimi, H. Al Neyadi, N. Mohamed, and J. Al-Jaroodi, "Applications of big data to smart cities," *Journal of Internet Services and Applications*, vol. 6, pp. 1–15, 2015.

[3] P. Mancarella, "Mes (multi-energy systems): An overview of concepts and evaluation models," *Energy*, vol. 65, pp. 1–17, 2014.

[4] Q. Alfalouji *et al.*, "Iot middleware platforms for smart energy systems: an empirical expert survey," *Buildings*, vol. 12, no. 5, p. 526, 2022.

[5] M. Luckner, M. Grzenda, R. Kunicki, and J. Legierski, "Iot architecture for urban data-centric services and applications," *ACM Transactions on Internet Technology (TOIT)*, vol. 20, no. 3, pp. 1–30, 2020.

[6] F. Arena *et al.*, "An innovative framework for dynamic traffic lights management based on the combined use of fuzzy logic and several network architectures," *Journal of Advanced Transportation*, vol. 2022, 2022.

[7] F. Zhu, Z. Li, S. Chen, and G. Xiong, "Parallel transportation management and control system and its applications in building smart cities," *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 6, pp. 1576–1585, 2016.

[8] F. R. Albogamy *et al.*, "Real-time energy management and load scheduling with renewable energy integration in smart grid," *Sustainability*, vol. 14, no. 3, p. 1792, 2022.

[9] A. Fakhar, A. M. Haidar, M. Abdullah, and N. Das, "Smart grid mechanism for green energy management: a comprehensive review," *International Journal of Green Energy*, vol. 20, no. 3, pp. 284–308, 2023.

[10] M. I. Khalil *et al.*, "Hybrid smart grid with sustainable energy efficient resources for smart cities," *sustainable energy technologies and assessments*, vol. 46, p. 101211, 2021.

[11] W. Velasquez, L. Tobar-Andrade, and I. Cedeno-Campoverde, "Monitoring and data processing architecture using the fiware platform for a renewable energy systems," in *Proc. of CCWC 2021*. IEEE, 2021, pp. 1383–1387.

[12] P. Qian, B. Feng, D. Zhang, X. Tian, and Y. Si, "Iot-based approach to condition monitoring of the wave power generation system," *IET Renewable Power Generation*, vol. 13, no. 12, pp. 2207–2214, 2019.

[13] M. S. Amin, "Ocean wave energy converter (wec) with iot applications," 2023.

[14] Y. Geng *et al.*, "An intelligent ieq monitoring and feedback system: development and applications," *Engineering*, vol. 18, pp. 218–231, 2022.

[15] G. Chiesa, A. Avignone, and T. Carluccio, "A low-cost monitoring platform and visual interface to analyse thermal comfort in smart building applications using a citizen–scientist strategy," *Energies*, vol. 15, no. 2, p. 564, 2022.

[16] M. Karami, G. V. McMorrow, and L. Wang, "Continuous monitoring of indoor environmental quality using an arduino-based data acquisition system," *Journal of Building Engineering*, vol. 19, pp. 412–419, 2018.

[17] "Iot analytics - thingspeak internet of things," https://thingspeak.com.

[18] G. Bracco, E. Giorcelli, and G. Mattiazzo, "Iswec: A gyroscopic mechanism for wave power exploitation," *Mechanism and machine theory*, vol. 46, no. 10, pp. 1411–1424, 2011.

[19] C. Győrödi, R. Győrödi, G. Pecherle, and A. Olah, "A comparative study: Mongodb vs. mysql," in *Proc. of EMES 2015*. IEEE, 2015, pp. 1–6.

[20] B. Jiang *et al.*, "Performance analysis and tank test validation of a hybrid ocean wave-current energy converter with a single power takeoff," *Energy Conversion and Management*, vol. 224, p. 113268, 2020.

[21] G. Reikard, "Integrating wave energy into the power grid: Simulation and forecasting," *Ocean Engineering*, vol. 73, pp. 168–178, 2013.

[22] R. N. F. Crespo *et al.*, "Lstm for grid power forecasting in short-term from wave energy converters," in *2023 IEEE 47th Annual Computers, Software, and Applications Conference (COMPSAC)*. IEEE, 2023, pp. 1495–1500.

[23] B. Lapillonne, C. Sebi, K. Pollier, and N. Mairet, "Energy efficiency trends in buildings in the eu," *Lessons from the ODYSSEE/MURE project. ADEME, Supported by Intelligent Energy Europe. Online at: http://www. odysseeindicators. org/publications/PDF/Buildings-brochure-2012. pdf*, 2012.

[24] "2011 buildings energy data book." [Online]. Available: https://ieer.org/wp/wp-content/uploads/2012/03/DOE-2011-Buildings-Energy-DataBook-BEDB.pdf

[25] M. L. Ruz, J. Garrido, and F. Vázquez, "Educational tool for the learning of thermal comfort control based on pmv-ppd indices," *Computer Applications in Engineering Education*, vol. 26, no. 4, pp. 906–917, 2018.

[26] A. Wald, "Statistical decision functions which minimize the maximum risk," *Annals of Mathematics*, pp. 265–280, 1945.

[27] "Communication networks and systems in substations–part 5: Communication requirements for functions and device models," *IEC 61850-5*, 2003.