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Design of a microservices-based architecture for residential energy efficiency monitoring

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***Abstract*—With the significant advancement of electrical infrastructure in the context of smart buildings and smart homes, the need arises to overcome the limitations of the traditional energy efficiency control system based on service-oriented architecture (SOA). To address these challenges, this study proposes a distributed architecture based on microservices, with the main objective of improving the performance and stability of these systems. This proposal seeks to enable end users to effectively monitor and control their electrical devices while effectively integrating them into a wide network of power systems. The proposed architecture relies on a series of cloud services that enable better performance and control in energy efficiency management, highlighting key features of microservices such as fault tolerance, performance, and scalability. Using a structural methodology centered on pre-existing components and an iterative approach, a versatile and scalable architecture was designed that addresses current challenges in energy efficiency management. The results show a significant impact on key performance indicators such as demand response, energy savings, and power quality, highlighting the resilience and scalability of the proposed architecture. The conclusions highlight the importance of energy efficiency in reducing the environmental impact and costs associated with electric power, suggesting future improvements in data access and the implementation of advanced machine learning algorithms.**

***Keywords*—Microservices; software architecture; energy efficiency; internet of things (IoT); smart homes**

I. INTRODUCTION

THE emerging business opportunities of the IoT are driving private, public, and hybrid cloud service providers to integrate their systems with IoT devices equipped with sensors and actuators to create an infrastructure that offers a whole new level of service capable of improving both the quality and security of the electricity supply [1], [2].

Simultaneously, the emergence of the IoT has led to a radical change in the design, implementation, and delivery of applications because of the continuous evolution of cloud computing. As a result, the prevailing need for efficient services and applications has driven Information and Communication Technology (ICT) operators to decentralize part of their services from the central data cloud to an intermediate layer closer to the user, known as the "Edge" [3], [4].

In this scenario, the concept of microservice or microservice architecture has gained a growing consensus in both industrial and academic communities because it enables the development of emerging cutting-edge IoT [5], [6]. This architecture style can promote effective separation between components and their adaptability to today's software needs for flexibility and dynamism, making applications easier to scale and faster to develop, enabling innovation, and speeding time to market for new features. This flexibility is particularly advantageous when integrating new technologies into existing systems. As technology evolves at a rapid pace, the ability to seamlessly incorporate new tools, frameworks, or paradigms into an application is invaluable. Microservice architecture, with its compartmentalized yet interconnected structure, is uniquely positioned to accommodate these technological advancements without the need for a complete overhaul of the system [7].

This research presents a proposal for a comprehensive and flexible microservices-based architecture that incorporates various ICT elements. This architecture aims to process consumption data recorded by low-cost meters in buildings and smart homes, building cloud computing by components such as IoT and mobile technology to enable users to access. Using Artificial Intelligence (AI) techniques, consumption data is analyzed, giving them the ability to improve the energy efficiency of their homes. This improves the understanding of energy consumption disturbances, including fluctuations dynamically introduced by system participants and facilitates planning that considers not only technical aspects but also the economic responses of participants to changes.

This research makes three fundamental contributions. First, it proposes a microservices-based architecture for energy management in smart buildings and homes, improving their efficiency and controllability. Second, it highlights the integration of the Internet of Things (IoT) and mobile technology in energy management, opening business opportunities and improving the quality and security of electricity supply. Finally, it promotes the concept of microservices as an efficient architectural approach to address challenges in emerging IoT applications, accelerating innovation and time-to-market in the era of cloud computing and IoT.

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The rest of the article follows a structure organized as follows: Section II presents the background, including a brief literature review, related work and relevant technologies. Section III discusses the materials and methods, detailing the methodology employed, the description of the problem and its motivation, as well as the proposed architecture to address it. Section IV presents the results obtained and discusses them. Finally, Section V presents the conclusions derived from the study, together with perspectives for future research.

II. BACKGROUND

A. *Literature review*

1) *Research Questions*: The research questions in this study focused on identifying work that could link microservices-based architecture to residential energy efficiency monitoring. In particular, this work focuses on two general questions: (1) How does the performance and scalability of a microservices-based architecture compare to other traditional architectures (such as SOA and monolithic) in residential energy efficiency monitoring systems? and (2) What impact does the implementation of a microservices architecture have on the flexibility and upgradeability of IoT systems for energy efficiency management in residential environments?

2) *Research process:* The present study has conducted an exhaustive review of the scientific and technical literature. To conduct this review, a rigorous process of research and selection of articles published in scientific journals and books in the last five years was used. The scientific databases used for this selection included Google Scholar, IEEE Xplore, SpringerLink, Science Direct (ELSEVIER), MDPI, and BASE (Bielefeld Academic Search Engine), using keywords in both English and Spanish, as shown in Figure 1. This rigorous methodological approach ensures the selection of reliable and relevant sources that support the purpose of the research, allowing an in-depth and up-to-date understanding of the topic of energy efficiency and electricity monitoring.

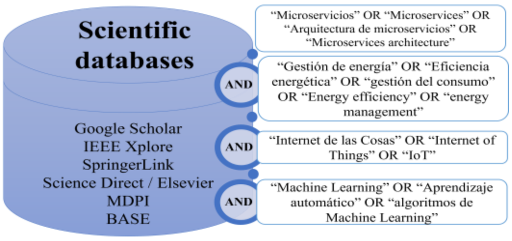


Fig. 1. Search String

3) *Filtering of studies:* The inclusion and exclusion criteria are fundamental to the filtering process since they allow us to identify the most relevant studies and discard those that do not contribute significantly to the literature review. The inclusion criteria (IC) defined for this work are as follows:

- IC1: The study must have been published in a peer-reviewed conference or journal.
- IC2: The study must be related to microservices architecture in the context of energy efficiency, smart buildings, smart homes, or smart cities.
- IC3: The study must be a full paper, i.e., no abstracts or preliminary presentations will be included.

Also, the following exclusion criteria (EC) were established:

- EC1: Studies that do not directly address research questions related to performance, scalability, flexibility, or upgradability of microservice architectures in energy efficiency monitoring systems will be excluded.

The central purpose of this literature review is to systemically compile relevant and up-to-date information to enrich understanding and progress in the field of energy efficiency. This objective is achieved by identifying the thematic areas of greatest interconnected and relevance within the set of 23 studies that have been subjected to the analysis [8], [9].

The flow diagram presented below in Figure 2 describes the process of selection and evaluation of articles as follows:

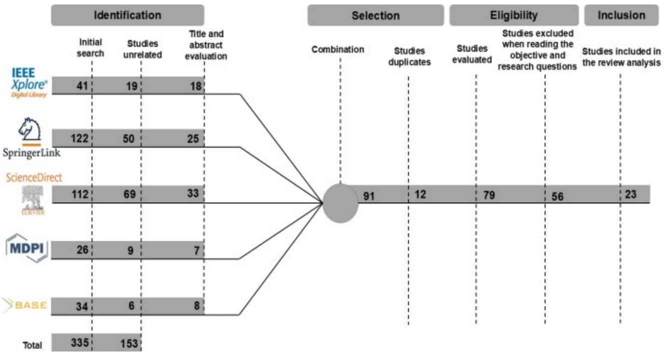


Fig. 2. Flowchart of analysis of scientific papers

- In the identification phase, the initial search was performed in the different databases, using keywords and search criteria.
- For the selection phase, all the articles were grouped, duplicate studies found in the different data sources were eliminated, and the articles were evaluated on the basis of the title and abstract.
- In the eligibility phase, the filtering was based on discarding those studies that were poorly related to the research approach. We then proceeded to the analysis and evaluation of the remaining articles, starting with translation, reading, and interpretation. The articles were characterized by extracting the title, country in which the study was conducted, year, language, abstract, introduction, objectives, sections, and subsections. Then, the synthesis of materials and methods was made, as well as the main results by carefully observing the figures, diagrams, and other illustrations, as well as the authors' recommendations.
- Finally, in the inclusion phase, those studies that were not very oriented to the objective and research questions of the review were excluded, and the articles to be analyzed were selected.

In order to provide a deeper insight into research trends in the field of microservices, a bibliometric analysis was performed using VOS viewer. This tool allows visualization of keyword co-occurrence networks and citation relationships between selected papers. The metrics analyzed included citation frequency, keyword co-occurrence index, and heat maps of author networks. Based on the bibliographic data extracted from the references included in this study, the relationships between the most frequent keywords and the connections between the cited papers were analyzed. The analysis revealed that terms such as “Internet of Things”, “microservices”, “cloud computing”, and “energy efficiency” are the most recurrent, highlighting the predominant trends in research. In addition, the citation networks showed a strong interconnection between studies focused on energy efficiency and microservices architecture. Figure 3 shows a graphical representation of the relationship between the different research topics.

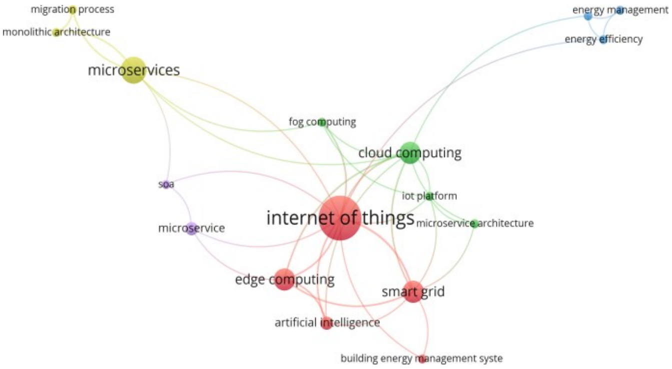


Fig. 3. Bibliometric visualization of results by keywords

B. *Related work*

In relation to the analysis performed, the increasing use of energy motivates researchers to look for options to improve traditional energy systems. According to one estimate, residential buildings and homes collectively consume about half of a grid’s total consumption [10], [11]. Considering the amount of consumption, efficient energy utilization within this sector can greatly reduce the load on a grid. Several research have proposed innovative solutions, such as an IoT smart meter as a service (IoTaaS) based on microservices to characterize nonlinear loads on the residential power grid and prevent failures [8], [12]). Other research has developed distributed smart home architectures, such as a smart gateway that manages the communication of home sensors with a central processor for further analysis [13], [14].

In addition, the transformation of power grid control system architecture from service-oriented (SOA) to microservices has been analyzed, addressing shortcomings such as scalability, maintainability, and speed of iteration [15], [16]. A microservices-based approach for building energy management systems (BEMS) has also been proposed, demonstrating improvements in performance and development [5], [17].

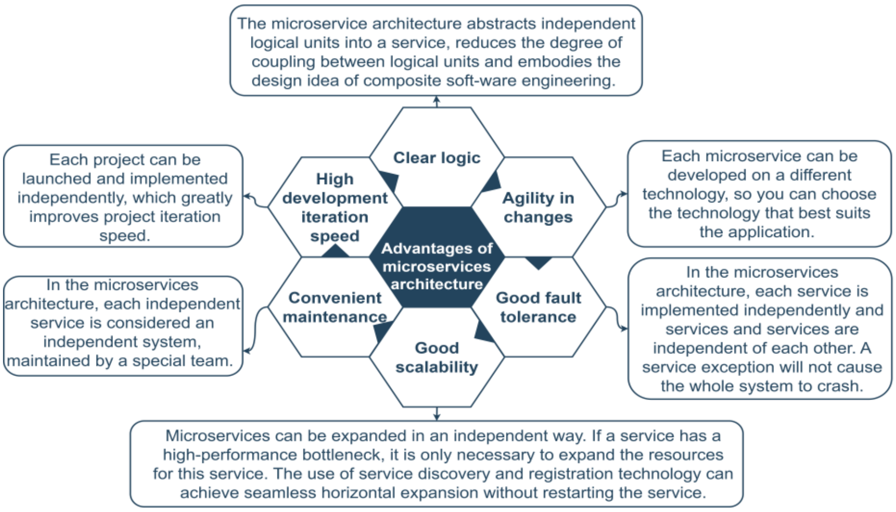
Finally, a microservices-based framework for integrating data sources into power grid management has been described, with results indicating improved performance and cost savings for large enterprises [18], [19]. These advances represent significant contributions to energy efficiency and energy management in buildings and power grids [20].

Based on these advances, the next logical step in improving energy systems is not only to monitor consumption but also to predict it. The ability to accurately predict energy consumption in residential and commercial environments has far-reaching implications for both energy providers and consumers [21], [22]. By using advanced analytics, machine learning algorithms, and real-time data processing, it is possible to predict future energy demand with a high degree of accuracy. This predictive capability enables more efficient distribution of energy, reducing waste and optimizing grid performance [23], [24]. For consumers, it means better management of energy costs and usage and a more personalized and responsive energy service [25].

Predictive models can also be an integral part of the integration of renewable energy sources into the grid, as they can predict the availability of these sources and adjust the grid load accordingly. Incorporating predictive analytics into energy systems goes beyond improving existing infrastructure [26], [27]. It paves the way for a smarter and more sustainable energy future, where energy supply is not only efficient but also anticipates and adapts to the ever-changing needs of the modern world [1], [9].

C. *Technologies*

- IoT in energy efficiency: In this proposal, IoT devices collect data on energy consumption, supporting the energy management systems. Buildings and homes require advanced monitoring of the quality of the power supply to ensure the continuity and efficiency of operations [23], [24], [26]. IoT is increasingly being integrated into the energy infrastructure of these environments, enabling the monitoring of key energy assets and the accurate measurement of energy consumption in individual units or appliances [20].
- Microservices: It is based on dividing the software into small independent services that communicate through well-defined interfaces. This allows it to handle technological variety and be resilient and scalable (see Figure 4) [6], [10]. Microservices are gaining popularity in the IoT and mobile technology fields because they help create robust and scalable systems that can adapt to new demands. They are especially useful for managing complex systems such as power grids because of their flexibility and adaptability. In this architecture, different protocols facilitate communication according to specific needs. HTTP/REST is simple and used for basic operations, while gRPC, developed by Google, offers better performance and advanced functionalities. GraphQL optimizes efficiency by allowing clients to define exactly the data structure they need. For asynchronous communications, message brokers such as RabbitMQ and Kafka are used. WebSockets are important for real-time bidirectional communications, and AMQP is robust for enterprise messaging systems. The choice of protocol depends on factors such as performance, data complexity, and scalability, and several protocols are often combined to meet different needs in microservices systems [21], [22], [28].
- Cloud computing: Through cloud computing technology, this architecture enables remote monitoring and edge computing. Thus transforming energy management in buildings and homes is significantly optimized. These



The microservice architecture abstracts independent logical units into a service, reduces the degree of coupling between logical units and embodies the design idea of composite soft-ware engineering.

Each project can be launched and implemented independently, which greatly improves project iteration speed.

Each microservice can be developed on a different technology, so you can choose the technology that best suits the application.

In the microservices architecture, each independent service is considered an independent system, maintained by a special team.

In the microservices architecture, each service is implemented independently and services and services are independent of each other. A service exception will not cause the whole system to crash.

Microservices can be expanded in an independent way. If a service has a high-performance bottleneck, it is only necessary to expand the resources for this service. The use of service discovery and registration technology can achieve seamless horizontal expansion without restarting the service.

Fig. 4. Advantages of microservices architecture

technologies enable more accurate monitoring and and greater efficiency in the use of electrical energy, which in turn contributes to reducing the environmental impact and costs associated with energy [18], [29].

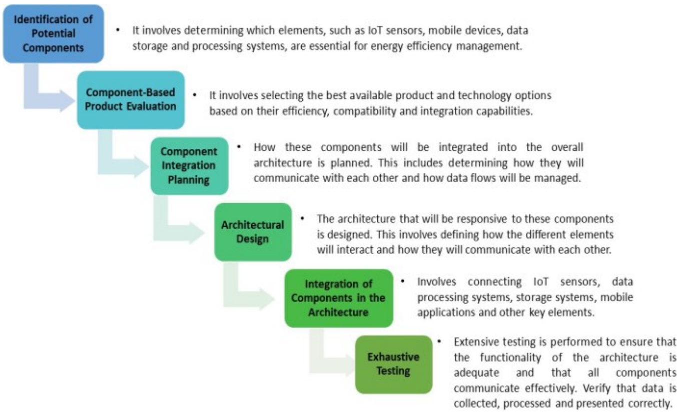
- Artificial Intelligence: Plays a key role in this architecture, allowing real-time problem detection and resolution in energy systems, significantly improving the reliability of these systems, and reducing maintenance costs. This transformation is based on advanced algorithms and machine learning techniques to optimize energy processes and systems. This optimization is achieved by meticulously identifying consumption patterns and proposing effective strategies aimed at reducing energy waste. AI systems can analyze large amounts of data to predict future energy demand with remarkable accuracy, not only understanding future consumption trends but also anticipating potential system failures or inefficiencies before they occur [7], [15].
- Mobile Apps: The use of mobile applications in energy systems has been integrated into the architecture of these systems, promoting ubiquitous computing. These applications allow users to manage and optimize their energy consumption from anywhere, offering accessible tools to monitor consumption in real-time, schedule devices at more efficient times, and access historical data to make informed decisions. They also facilitate remote control of devices, improving energy management even when users are away from home. This approach reflects the trend towards smarter, more connected living spaces, where convenience and efficiency are paramount [27].

III. MATERIALS AND METHODS

A. *Methodology*

The methodology proposed for this research is based on a structural software architecture model, centered on the use of components.

A. This approach involves the construction of applications from pre-existing software fragments, adopting an iterative and evolutionary process. The methodology begins with the identification of potential components, integrating steps such as the evaluation of products based on existing components, the planning of the integration of these components, and the design of a software architecture that adapts to these elements. The components are then integrated into the proposed architecture, followed by extensive testing to ensure proper functionality. This methodology is particularly relevant for addressing problems in energy efficiency management in buildings and smart homes, focusing on creating an architecture that is versatile, scalable, and efficient in terms of energy data processing and analysis [12]. Figure 5 below details the key aspects of this methodology.



- It involves determining which elements, such as IoT sensors, mobile devices, data storage and processing systems, are essential for energy efficiency management.
- It involves selecting the best available product and technology options based on their efficiency, compatibility and integration capabilities.
- How these components will be integrated into the overall architecture is planned. This includes determining how they will communicate with each other and how data flows will be managed.
- The architecture that will be responsive to these components is designed. This involves defining how the different elements will interact and how they will communicate with each other.
- Involves connecting IoT sensors, data processing systems, storage systems, mobile applications and other key elements.
- Extensive testing is performed to ensure that the functionality of the architecture is adequate and that all components communicate effectively. Verify that data is collected, processed and presented correctly.

Fig. 5. Block diagram of the methodology used

The component-based architecture approach is based on the premise that the overall architecture is composed of individual elements or components, each with specific functions. These components can be either physical (such as sensors and servers) or software (such as microservices). In addition, a data

TABLE I
COMPARISON OF SOA, MICROSERVICES, MONOLITHIC, LAYERED, AND EVENT-DRIVEN ARCHITECTURES

Aspect	**SOA**	**Microservice**	**Monolithic**	**Layered**	**Event-Driven**
Architecture	Built as a single logical executable	Built as a suite of small services, each running separately and communicating with lightweight mechanisms	All components combined into a single code-base	Organized in layers, where each layer has a specific role	Built around the production and consumption of events, often asynchronous
Modularity	Based on language features	Based on business capabilities	Minimal modularity; difficult to isolate components	Modular within each layer, but dependencies can become complex	Highly modular, focusing on loosely coupled event processors
Agility	Changes to the system involve building and developing a new version of the entire application	Changes can be applied to each service independently	Changes require rebuilding and redeploying the entire application	Changes within a layer are easier, but cross-layer changes can be cumbersome	Very agile; new events and processors can be added with minimal disruption
Scaling	Entire application scaled horizontally behind a load-balancer	Each service is scaled independently when needed	Limited to vertical scaling or entire application horizontal scaling	Scaling requires careful management of inter-layer communication	Scales dynamically based on event traffic and processor capacity
Implementation	Typically written in one language	Each service implemented in the language that best fits the need	Typically implemented in a single language	Typically implemented in a single language, with clear separation between layers	Language agnostic; each event processor can be implemented in the most suitable language
Maintainability	Large code base intimidating to new developers	Smaller code base is easier to manage	Large code base; difficult to maintain and on-board new developers	Easier to maintain within layers, but can be complex due to interdependencies	High maintainability due to loose coupling and clear responsibilities
Resilience	A failure in any component could affect the availability of the entire application	If one microservice fails, the functionality provided by the other microservices is still available	A failure can bring down the entire system	Failure in one layer can propagate to other layers	High resilience; failures are often isolated to specific events or processors
Data management	Centralized: the entire application uses one or more databases	Decentralized: Each microservice can use its own database	Centralized; one or more databases shared across the application	Centralized or per layer; often tied to the overall structure of the application	Decentralized; each event processor may handle its own data storage or rely on external system

persistence pattern is adopted to design the architecture, in which the various components operate as independent microservices. Each microservice, in charge of a specific function, communicates with others through clearly defined interfaces, commonly via HTTP APIs. This model favors scalability, flexibility, and adaptability of the architecture, allowing independent development and deployment of each microservice. This strategy is essential to avoid the problems associated with monolithic software systems, where a single large and complex component manages all functionality [3], [13].

B. Problem statement and motivation

Grid management in smart buildings and smart homes faces increasing challenges due to the need to meet diverse user demands, ensure collaboration between disparate systems, and comply with increasingly stringent security requirements. In this context, service-oriented architecture (SOA), although widely used, has fallen short of meeting today's reliability and performance standards required for efficient energy control. This limitation has led to the proposal of a microservices-based architecture as a viable alternative.

Microservices-based architecture offers a more effective way to manage energy efficiency in buildings and smart homes. One of its main advantages is its ability to simplify the underlying complexity of the system. By decomposing the system into smaller, manageable, and independent services, each with a specific function, the microservices layer hides the complexities from both users and developers. This not only facilitates the development and maintenance process but also improves the agility and scalability of the system, making it more adaptable to changing requirements and technological advances in smart grid management.

To achieve these objectives, the implementation of an IoT device for smart metering and a mobile application that incorporates microservices capable of processing the data coming from the electrical network of a building are contemplated. The measured variable is electricity consumption, recorded by sensors in the home, which indicates electricity consumption over a period of time in kilowatt-hours (kWh). In addition, artificial intelligence predictive models are used for analysis, control, and prediction of power quality, facilitating more efficient management of the power grid in smart environments. This proposal offers an innovative perspective that supports decision-making based on data analysis through robust systems with predictive capabilities, thanks to the application of microservices in real-time

Microservices architecture and SOA divide the system into services but in different ways. From an implementation perspective, SOA can look like a monolith, while microservices result in independent implementations. In industry, microservices are associated with container technologies that simplify automated deployment. Containers are fundamental to creating these independent deployment units of microservices. In addition, microservices architecture promotes design autonomy, with many small teams resulting in heterogeneity of components.

Beyond SOA and microservices, it is essential to consider other architectural paradigms, such as Monolithic, Layered, and Event-Driven architectures, especially in the context of energy efficiency management and optimization in smart buildings or smart homes. Monolithic architecture, while straightforward in development and deployment, can become rigid and difficult to scale in dynamic IoT environments. Layered architecture, with its clear separation of concerns, improves maintainability but may introduce overhead that limits responsiveness. On the other hand, Event-Driven architecture excels in real-time processing and adaptability, making it highly suitable for IoT scenarios, though it brings added complexity in ensuring data consistency.

A brief comparison between service-oriented architecture (SOA) and microservices-based architecture for energy efficiency management and optimization in smart buildings or smart homes is presented in Table I, with additional consideration of Monolithic, Layered, and Event-Driven architectures to provide a more comprehensive understanding of their re- respective strengths and weaknesses in these contexts.

C. Proposed architecture

This study proposes a microservices-based architecture for power grid management in building complexes and residential areas, enabling collaborative cloud-based management of components that iteratively develop and update services. The architecture seeks to improve the reliability, quality, and efficiency of the power supply by integrating storage technology, demand analysis, and power consumption control.

It employs a fusion of computational paradigms, combining Edge and Cloud in a hybrid cloud architecture, supporting the deployment of high-performance applications using the microservices pattern (see Figure 6). Key benefits include reduced costs, versatility in software quality, configurable scalability and adaptability on demand, compatibility with various devices and protocols, and a REST API-based framework for integration with microservices and applications.

The architecture is divided into five functional layers:

1) IoT Layer (IoT Sensor): Monitors energy assets through IoT devices, including a low-cost electric meter. This allows capturing essential data for visualization in the application and training AI models, improving energy efficiency.
2) Processing Layer: Uses microservices that communicate via REST to allow access from devices such as smartphones and tablets through an API gateway and from computers through user interfaces (UI).
3) Network and Data Storage Layer: Establishes connections and stores data in distributed databases, managing structured and unstructured data in a persistent manner [30]. Structured data, usually organized in a tabular format with defined rows and columns, is stored in relational databases. This format is ideal for data that conforms to a predefined schema, such as meter readings, user profiles, and transaction logs, allowing efficient querying and processing. On the other hand, unstructured data, which includes a variety of formats such as text, images, and sensor data, is stored in non-relational databases (NoSQL). These databases are designed to handle the flexibility and scalability needed for large volumes of diverse data that do not conform to a fixed schema. Unstructured data storage is particularly important in smart grid systems, as it encompasses a wide range of data types, from IoT sensor outputs to user interaction logs [30]. By effectively managing both structured and unstructured data, the network and data storage layer ensures a complete and versatile data ecosystem. This ecosystem is essential for the

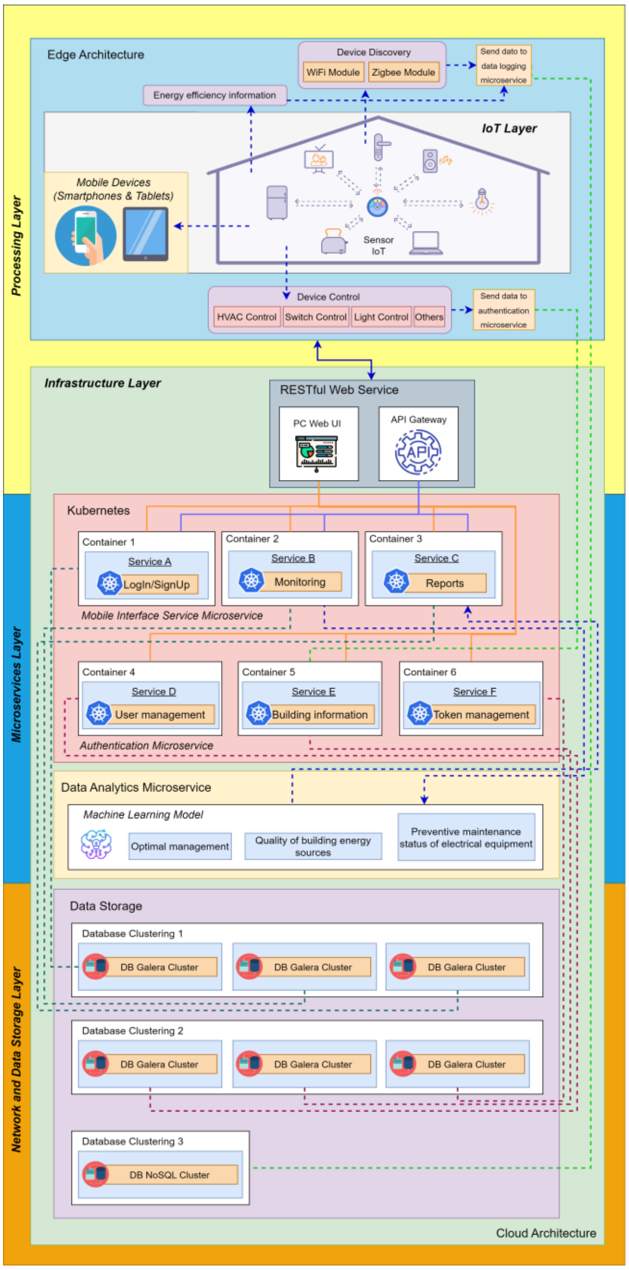


Fig. 6. Proposed system architecture

efficient operation of smart grid systems, enabling advanced data analytics, machine learning applications, and real-time decision-making processes. The ability to handle diverse data formats and structures in a persistent manner underpins the robustness and adaptability of the smart grid management infrastructure.

4) Infrastructure Layer: manages communication, scalability, and availability of data across cloud servers, networks, and components. It provides network, server, and storage resources, relieving the load on the cloud with Docker containers and load balancers (NGINX). It also handles complex tasks such as authentication and interoperability.
5) Microservices Layer: Contains essential microservices, such as authentication, device discovery, device control, monitoring, data logging, interfacing, and data analysis. Each one fulfills a specific role, such as controlling access, discovering new devices, changing device operations, monitoring status, storing data, and providing a user interface. Within this layer, we find key microservices such as:

- Energy efficiency calculation microservice: This variable measures the amount of energy used by a device or appliance to perform a specific task. It is defined as the ratio between the desired output (e.g., the amount of light emitted by a light bulb) and the energy consumed to produce that output. In this context, the microservice dedicated to the calculation of energy efficiency is used. The process starts with the collection of data from sensors, which record both input energy and output energy. This data is sent to the microservice, where the energy efficiency equation 1 is applied to determine the efficiency value. The result obtained is displayed on the user interface or used for other purposes, such as energy system optimization or consumption analysis.

$$Efficiency = \frac{Outputenergy}{nputenergy} 100\% \tag{1}$$

- Load Prediction Model Microservice: This microservice is used to predict load as a function of predictor variables. A polynomial regression model is proposed which allows to fit non-linear relationships. It is used to model the predicted load (Y) as a function of predictor variables (X) using a polynomial equation 2 and the result (predicted load) is returned for use in the application.

$$Y = aX^2 + bX + c \tag{2}$$

Where a, b, and c are coefficients that fit the data.

- Microservice Fault Tolerance calculation: It is used to represent the fault tolerance of the microservice based system, considering the number of microservices (N) and the probability of a microservice failure (Pf), this value can help in making decisions related to fault tolerance and redundancy in the architecture (3):

$$Fault\_Tolerance = (1 - Pf)^N \tag{3}$$

Where F ault T olerance is the probability that the entire system functions without failures. P f is the probability of failure of an individual microservice.

- Microservice scalability calculation: Represents the scalability of the microservice-based system using the equation that considers the load (C) and the capacity of a microservice (S), this value can be useful to properly size the resources and ensure that the system can handle the demand (4):

$$Scalability = \frac{C}{S} \tag{4}$$

Where: Scalability is the ability of the system to handle the load, C is the current load on the system and S is the capacity of an individual microservice.

- Data Analysis Microservice: A Logistic Regression model for Energy Efficiency is employed, which is used to model the relationship between predictor variables (X) and the probability of a binary outcome (Y), The result (probability of energy efficiency) is returned for use in decision making or visualization (5):

Where: $P(Y = 1)$ is the probability that Y is equal to 1, y $X_1, X_2, \ldots, X_n$ are the predictor variables and $\beta_0, \beta_1, \beta_2, \ldots, \beta_n$ are the regression coefficients.

$$\log \frac{P(Y=1)}{1 - P(Y=1)} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n \tag{5}$$

- User Management Microservice: This microservice is responsible for handling user authentication, authorization, and user profile management. It ensures secure access to the system and manages user related data. It can include functionalities such as user registration, login/logout, password management, role-based access control, and user profile management.
- Device Control Microservice: This microservice is responsible for managing device operations, including device discovery, device control, and status monitoring. It facilitates communication between the user interface and the devices, allowing users to interact with connected devices. Functionalities may include device registration, device status monitoring, device control, and handling device events.

All interactions are managed through the REST API gateway, which acts as a proxy for the microservices, enabling additional functionalities such as caching and monitoring. In addition, interactions are independent of physical hosting, ensuring robustness to failures at different layers of the architecture.

IV. RESULTS AND DISCUSSION

As a result of this research, the proposed architecture has a significant impact on the key performance indicators of a smart building or smart home. This impact has been illustrated through a performance case in which the cloud computing instance was used as a platform. In the context of a smart home equipped with IoT sensors, energy efficiency data is captured from devices such as light bulbs, appliances, and electronic locks. This data is managed and stored in an IoT platform for further processing using various microservices.

Table II shows the data used to train the Load Prediction Model Microservice model. These data were stored in Pandas DataFrame and were programmed using Python. To train the models, 80 of the data was used and 20 was used in testing.

TABLE II
SIMULATION TIMES OF EACH SCENARIO

	Consumption	Prediction
0	766.139435	691.866765
1	240.378564	213.752675
2	368.095888	411.995102
3	566.864165	563.592253
4	219.383939	155.446079

The graphical representation of the prediction model on residential electricity consumption data is shown in Figure 7. The coefficient of determination r^2 is used in regression models to evaluate how well the test data fit the model. The optimal fit is achieved when a value of 1 is reached in this coefficient. For this model developed, the coefficient of determination (r^2) was 0.9449.

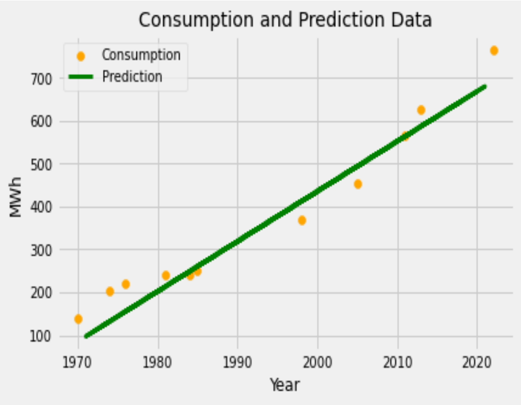


Fig. 7. Consumption and Prediction Data Model

The main objective of this architecture is to achieve:

- Demand Response: The architecture enables a quick and effective response to changing energy demands in a building, optimizing its use.
- Energy Savings: Facilitates the identification of energy savings opportunities by analyzing energy efficiency data
- Variable Condition Load Forecasting: Uses predictive models to anticipate future energy loads, which aids in efficient planning and management.
- Optimal Management: Provides a clear and complete view of the systems in the network, enabling more effective management and preventive actions for maintenance.
- Quality of Energy Sources: Monitors the quality of energy sources to ensure a stable and reliable supply.
- Preventive Maintenance of Electrical Equipment: Facilitates preventive maintenance by providing real-time information on the status of electrical devices.

Furthermore, after obtaining future predictions on energy efficiency using microservices, users are offered an interface through mobile devices, as shown in Figure 8. This interface allows users to access detailed statistics on energy consumption and to control the household's electrical energy remotely. This is presented as a service for end customers in the context of an energy management system.

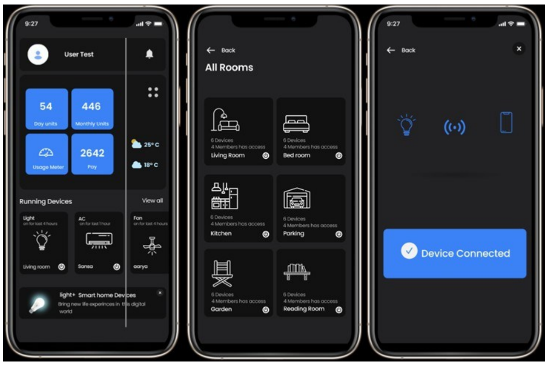


Fig. 8. Power management system interface prototype.

To accurately compare the performance of the proposed microservices vs. SOA and monolithic architecture, a simulation was performed by setting up a controlled test environment. In this environment, a robust test server with 8 virtual cores, 32 GB of RAM, and 1 TB of SSD storage was used. The server is capable of running multiple virtual machines (VMs), each representing an instance or node of the system to be tested. These VMs run on a hypervisor such as VirtualBox and use Ubuntu Server 22.04 LTS as the operating system to ensure uniformity in configuration.

On the software side, the architectures were deployed using different tools. Microservices were run in Docker containers, with Kubernetes to manage orchestration and scalability. For SOA, application servers such as Apache Tomcat were used, while the monolithic application would be deployed on a similar application server. All architectures used a centralized database, such as PostgreSQL, deployed in a separate VM. In addition, monitoring tools such as Prometheus and Grafana were essential to track resource usage, such as CPU, memory, and network, providing a real-time view of system performance.

To evaluate performance, load testing tools such as Apache JMeter were used. These tools allowed simulating traffic and measuring response times under different load levels, starting with low loads and gradually increasing to very high levels. During these tests, the scalability of the architectures was observed by adding additional instances or containers for microservices and configuring clusters for SOA. The data collected through Prometheus was analyzed and visualized in Grafana, facilitating the generation of graphs and reports comparing the performance of the different architectures in terms of response time, scalability, and resource usage.

Table III shows the comparison with the key metrics for each architecture.

TABLE III
PERFORMANCE COMPARISON

Metrics	Microservices	SOA	Monolithic
Response Time	200 ms	350 ms	500 ms
Scalability	High (linear)	Medium	Low
CPU utilization	40%	60%	70%
Memory Usage	200 MB	300 MB	400 MB
Bandwidth Usage	50 Mbps	70 Mbps	100 Mbps

The figure 9 shows a line graph of how response time increases with increasing load for each architecture and the degree of scalability in performance relative to the number of instances or nodes.

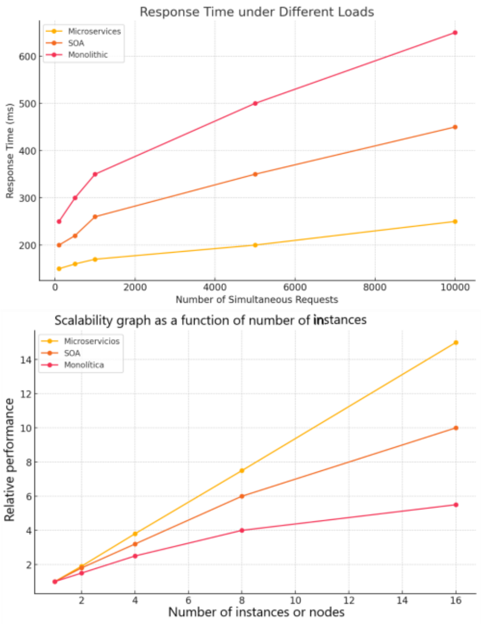


Fig. 9. Response time and scalability

This testing environment ensured that comparisons between the different architectures are fair and replicable, providing accurate data on how each performs under similar conditions. The combination of modern monitoring and load testing tools ensures that the results accurately reflect the actual performance of each architecture, which is crucial for validating the superiority or disadvantages of the proposed microservices architecture compared to existing methods.

The microservices-based architecture, evaluated by key metrics, stands out for its resilience and scalability, as it allows different components, such as device control, to remain operational even if one fails, mitigating the risk of cascading failures. In addition, it optimizes software resources by efficiently managing both current and future resources, especially in dynamic contexts such as demand response events.

It also facilitates the rapid integration of new devices and APIs, crucial for smart home and smart building systems that require agile adaptations to technological innovations.

V. CONCLUSIONS

Energy efficiency is critical to reducing the environmental impact and costs associated with electrical energy, and accurate monitoring of electricity consumption enables users to make informed decisions to optimize their energy use and reduce waste. The research has shown that microservices-based architecture has a positive impact on energy efficiency and smart building management by providing a versatile and scalable platform for energy data collection, processing, and analysis, as well as end-user interaction.

The results obtained have practical applications in energy efficiency management in smart buildings and smart homes, which can translate into significant energy savings, more efficient response to energy demand, and improved quality in the management of electrical resources. The impact of this work on the scientific community lies in the introduction of an innovative architecture for energy management in smart environments and in the identification of the limitations of traditional architectures. These contributions may inspire further research and advances in the field of energy management in the era of IoT and emerging technologies.

For future work, it is recommended to apply and improve the proposed architecture to increase data access, enabling more advanced machine learning algorithms. In addition, it is suggested to explore new IoT technologies and software-driven energy service transactions for even more effective optimization of energy efficiency.

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