NATIONAL UNIVERSITY OF SCIENCE AND TECHNOLOGY POLITEHNICA BUCHAREST
FACULTY OF POWER ENGINEERING

Doctoral School of Power Engineering

PhD THESIS

RESEARCH ON INTEGRATED ENERGY MANAGEMENT SYSTEMS IN BUILDINGS

Author: PhD. Eng. Ștefăniță PLUTEANU
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List of figures

Table of Contents

1. Introduction

The technological advancements of recent decades have led to significant changes in energy management, emphasizing the need for integrated solutions to optimize consumption in residential and tertiary buildings. The integration of energy management systems based on emerging technologies, such as the Internet of Things (IoT) and the Internet of Energy (IoE), represents a key direction in increasing energy efficiency and reducing environmental impact.

In this context, the present thesis aims to research and develop innovative solutions for integrating intelligent systems for monitoring and optimizing energy consumption, with the fundamental objective of enhancing sustainability and operational efficiency within modern infrastructures.

One of the novel aspects of this research lies in the development and implementation of a modular and scalable system that can adapt to technological advancements and ensures a high level of granularity in the data collected and monitored in real time. This system enables an accurate evaluation of energy performance and contributes to a detailed understanding of consumption patterns, facilitating data-driven decision-making for optimizing resource utilization. By integrating energy consumption prediction technologies and Demand-Side Management (DSM) programs, the proposed solution provides a modern framework for improving the relationship between consumers and suppliers.

1.1. Context and relevance of the study

The efficient management of energy resources is one of the major challenges of modern society, having a direct impact on both economic and environmental sustainability. Buildings account for a significant percentage of global energy consumption, and optimizing them through the integration of smart technologies has become a strategic priority. In this regard, intelligent energy management, based on advanced monitoring, digital prediction, and automation, represents a viable solution for reducing energy losses and increasing energy efficiency.

The development of IoT and IoE technologies has facilitated the transition to smart energy management systems, which enable real-time data collection and analysis, providing a detailed perspective on consumption patterns and optimization opportunities. In this context, the present thesis examines the benefits brought by these technologies, as well as the challenges associated with their implementation in modern infrastructures.

Additionally, this research highlights the necessity of implementing DSM programs, which facilitate a more balanced use of energy, benefiting both consumers and energy providers. By integrating these approaches, efficient solutions can be developed for managing energy consumption in residential and tertiary buildings, contributing to a reduction in the carbon footprint and the optimization of operational costs.

1.2. Adopted research methodology

In this thesis, a structured methodology has been developed for the implementation and analysis of integrated energy management systems, with the aim of optimizing energy consumption and increasing the efficiency of existing infrastructures. This methodology is based on a multidisciplinary approach that combines IoT technologies, predictive analytics, and process automation. By integrating modular and scalable architectures, the proposed methodology allows the solution to be adapted to different types of buildings and operational requirements, ensuring flexibility and efficiency in application.

A key aspect of the methodology involves developing a structured implementation strategy for an integrated energy management system. This includes:

- Identifying the system's needs and objectives,
- Establishing the network topology and communication protocols,
- Defining the hardware and software infrastructure,
- Configuring and installing equipment,
- Implementing the management, visualization, and data processing system,
- Integrating predictive algorithms to provide forecasts for energy consumption optimization,
- Implementing energy efficiency solutions.

Regarding the economic impact analysis, the methodology includes a general evaluation of the financial benefits of the proposed solution. Estimates were made regarding the efficiency of system implementation, including an analysis of initial costs and the identification of potential savings resulting from energy consumption optimization. This evaluation provided insight into the system's profitability.

Finally, the proposed methodology was validated through the results and simulations conducted at the POLITEHNICA University of Bucharest campus. These tests demonstrated the solution's ability to improve energy consumption management and provide higher granularity in monitoring. The practical validation of the solution confirmed the applicability of the proposed methodology in complex infrastructures.

1.3. Impact of results

The results obtained in this research demonstrate that integrating an intelligent energy management system leads to a significant reduction in energy consumption and CO_2 emissions. Granular consumption monitoring allowed for the identification of inefficiencies, while the implementation of predictive algorithms contributed to optimizing resource utilization.

An important aspect of this research is that the developed solutions can be extended and adapted to various types of buildings, offering a scalable model for energy consumption optimization. Moreover, the integration of DSM (Demand-Side Management) programs can facilitate better collaboration between consumers and providers, improving the management of energy demand.

2. Current state of technology and trends in energy management

This chapter presents a review of the specialized literature on current technologies and trends in integrated energy management. It discusses European and national regulations on energy efficiency in buildings, emphasizing the challenges encountered in integrating modern energy systems. The chapter also explores current technological solutions for energy monitoring and efficiency, as well as the importance of integrating IoT technologies for effective energy management.

2.1. European and national regulations on energy efficiency in buildings

This subsection addresses European and national regulations concerning energy efficiency in buildings, aiming to reduce energy consumption and carbon emissions.

National legislation transposes the regulations imposed by the European Union regarding energy efficiency in buildings. These regulations are integrated into the national legislative framework through strategies and programs designed to improve energy efficiency in both existing buildings and new constructions. Implementing these measures at the national level presents technical and economic challenges, yet it is essential for ensuring compliance with European objectives to minimize energy consumption and reduce the carbon footprint.

In 2022, the final energy consumption in the EU was 37,771 PJ, with the industrial sector accounting for 25.1% of the total, while households represented 26.9% [1]. The tertiary sector, largely comprising services, plays a significant role in the building sector and accounted for 9.0% of the EU's final energy consumption. [1]

Within the European Union, buildings account for approximately 40% of total energy consumption and are responsible for 36% of greenhouse gas emissions. Moreover, it is estimated that three-quarters of these buildings are not energy efficient. [2]

Romanian legislation on the implementation of smart metering systems for electricity flow mandates the integration of consumption points into smart metering networks, thus facilitating bidirectional data transfer. [3]

This legislative framework highlights the importance of smart metering in improving energy management and efficiency.

2.2. Current technologies for energy consumption monitoring and optimization

The integration of IoT devices and BIM (Building Information Modeling) solutions represents a significant development direction in the field of energy management systems. Complementing BIM, IoT technologies play a crucial role in monitoring and managing energy consumption throughout the entire building lifecycle.

By collecting data from IoT devices and integrating it with BIM models, buildings can be monitored and controlled more effectively. This approach enables efficient virtualization of buildings, improving performance and adaptability to dynamic energy requirements in the context of energy efficiency solutions. IoT provides real-time data on energy consumption and system status, while BIM structures this data within a 3D model of the monitored building.

A **Building Energy Management System (BEMS)** can be built based on IoT and BIM integration, structured across multiple levels, similar to the **TCP/IP model**. This integrated model allows for the optimization of resource utilization and adaptation to changes in the built environment, enhancing energy efficiency and reducing environmental impact.

The integration of IoT technologies into energy management systems opens new opportunities for intelligent and optimized resource management. Due to their size and complexity, **university campuses** provide an ideal setting for implementing and testing these solutions, with the potential to highlight the long-term advantages of these innovations. [6]

An essential concept for integrating IoT technologies into management systems with complex requirements is **"edge computing"**. In this model, data generated at the local level is processed either on physical devices or transmitted to central servers for analysis and decision-making. Figure 2.1 illustrates the IoT data flow based on the "edge" computing concept.

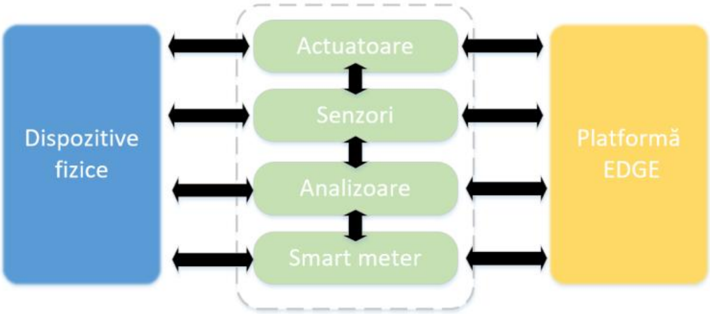

Figure 2.1 *IoT data flow based on the "edge" computing concept*

Edge platforms are crucial in aggregating and processing data from local networks, enabling the management of connected applications and devices, thus providing comprehensive and integrated IoT solutions. Additionally, these platforms can be connected to other external IoT systems to extend management and data analysis capabilities to a higher level.

3. Architecture of integrated energy management systems based on IoT

This chapter presents the architecture of IoT systems used in integrated energy management systems. The role of IoT and Internet of Energy (IoE) in optimizing energy consumption is analyzed from the perspective of network topologies and architectures. Key aspects discussed include communication protocols, data transmission security solutions, and technologies used for data monitoring and processing. Additionally, the hardware and software structure of intelligent energy management systems is presented in the context of monitoring and controlling energy flows.

3.1. Architecture and topologies of IoT networks for integrated Systems

A network architecture consists of a topology, a type of cable, an access method, and a communication protocol. IoT architecture, compared to the OSI and TCP/IP models, demonstrates the different layers involved in data communication and processing (Figure 3.1).

The IoT network includes sensors, smart meters, and actuators connected through gateways, PLCs, and routers to ensure a seamless flow of data and communication across the entire system. The sensors deployed at each site are responsible for collecting real-time data on energy consumption and environmental parameters, which are then transmitted to the central server via MQTT for processing and analysis.

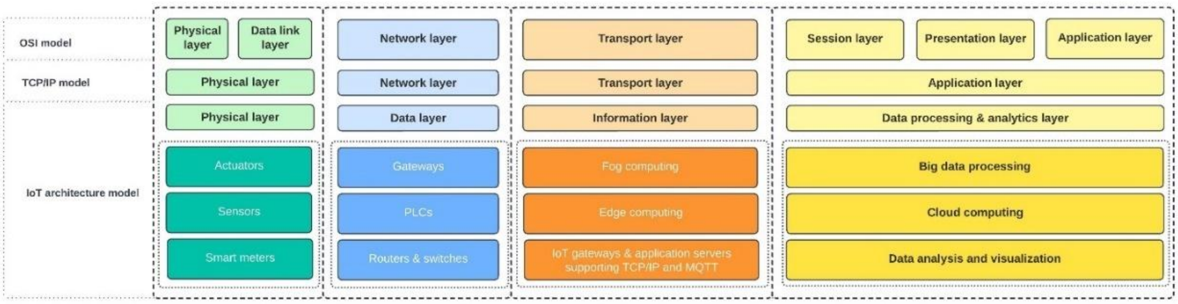

Figure 3.1 *IoT Architecture Compared to OSI and TCP/IP Models*

The proposed logical flow diagram for the IoT architecture (Figure 3.2) outlines the interaction between the system's various components. [7]

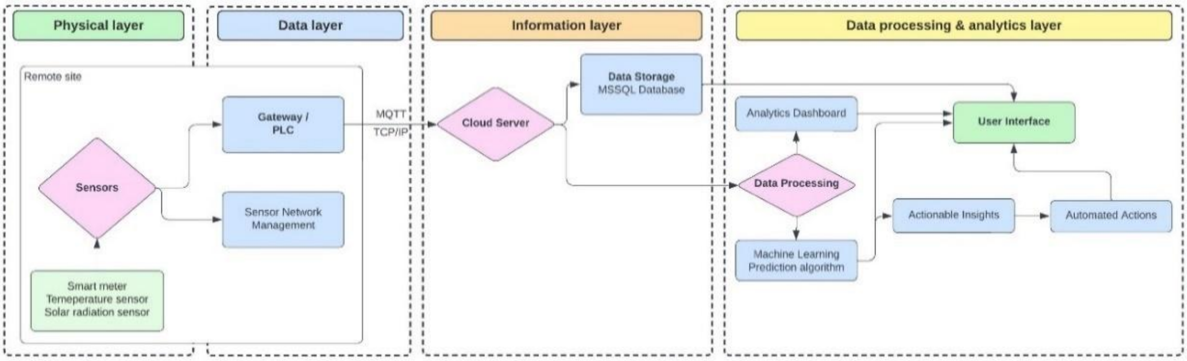

Figure 3.2 *Logical Flow Diagram for an IoT Network*

In the modern context of smart buildings and energy efficiency, the architecture of intelligent energy management systems plays a crucial role in resource optimization and operational cost reduction. At the core of these solutions are technologies such as VMware ESXi, a bare-metal virtualization platform that offers flexibility and redundancy in IT resource management.

In Figure 3.3, a virtualized server architecture is presented.

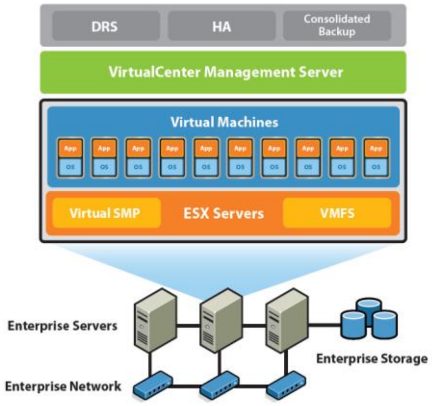

Figure 3.3 *Virtualized Server Infrastructure [4]*

3.2. Real-time data monitoring and processing

This subsection analyzes the methodology implemented for data collection, processing, and interpretation in an IoT-based integrated energy management system. The network architecture, communication protocols, and data processing methods for optimizing energy consumption are highlighted. The integration of IoT technologies allows for a high level of information granularity, facilitating anomaly detection and real-time data-driven decision-making.

A control, monitoring, and data processing solution is based on IoT architecture. The solution is designed to communicate with the IoT monitoring system, which exchanges data with the control unit via Message Queuing Telemetry Transport (MQTT) and RESTful API web services. The IoT network uses a central server that aggregates data from smart meters and sensors via communication protocols.

The IoT architecture is built on multiple layers, each playing a specific role in data processing. The communication layer uses protocols such as Modbus to transmit data from smart meters to control units, and then to the central server via MQTT and TCP/IP for continuous analysis and monitoring. This system enables predictive analysis and real-time monitoring of energy consumption.

Data collected from the IoT network is monitored and analyzed using Node-RED, an open-source platform that allows data visualization and management through a node-based workflow. Node-RED is used to aggregate, process, and transmit data from smart meters to a central server, where it is integrated into a Microsoft SQL database for detailed analysis.

A Node-RED data flow example is illustrated in Figure 3.4, where each energy meter is connected via an individual node. These nodes are configured to collect data from smart meters and transmit it to preprocessing functions or aggregate data over predefined time intervals. Once the data is processed, it is sent to the central node, which integrates it into a format suitable for storage in the SQL database.

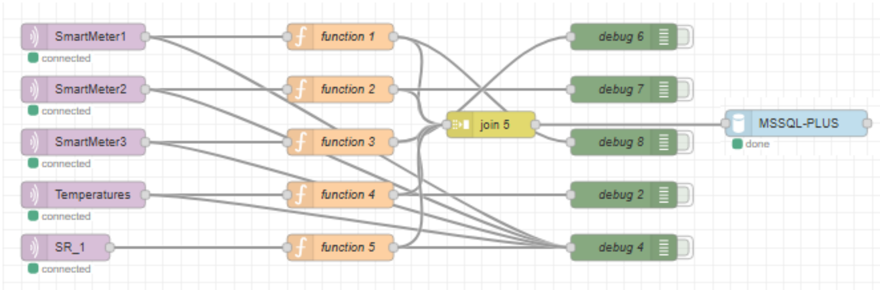

Figure 3.4 *Data Aggregation Using Node-RED*

Another key aspect of the monitoring process is the use of data visualization platforms, such as the open-source solution Grafana, which provides an intuitive interface for interpreting and analyzing energy consumption trends (Figure 3.5).

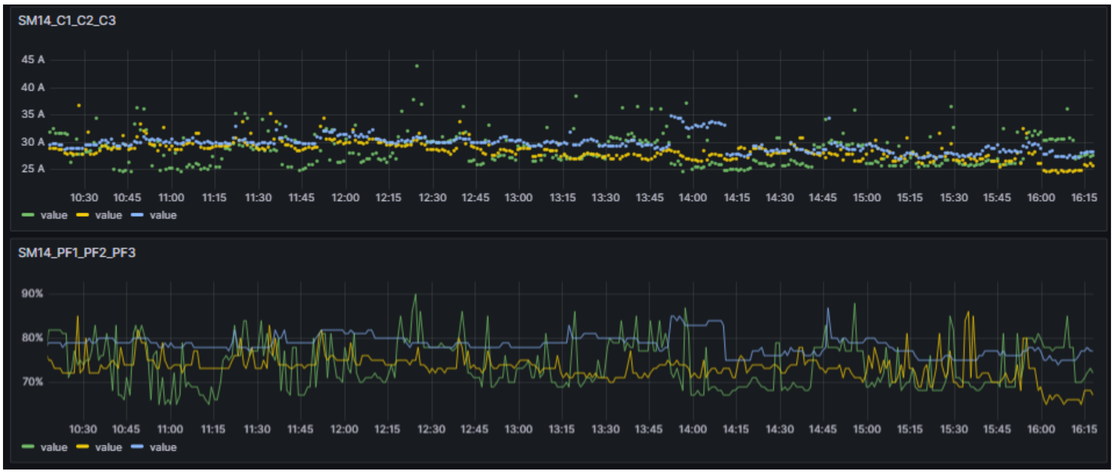

Figure 3.5 *Data Visualization in Grafana Platform*

4. Prediction algorithms and energy consumption optimization

This chapter discusses various methods and algorithms for predicting and optimizing energy consumption. The machine learning algorithms covered include linear regression, the ARIMA model, and the LSTM model, all of which are used to estimate energy consumption patterns.

4.1. Calculations assumptions and methods using prediction algorithms

This subsection discusses three main predictive models: linear regression, ARIMA, and LSTM neural networks, each playing a role in forecasting future trends based on historical energy consumption data.

The use of these models is essential for optimizing energy consumption, being integrated into intelligent energy management systems within the campus. Based on real-time collected data and the algorithms' ability to learn from previous data, more precise predictions can be made, allowing for dynamic consumption adjustments. Each model presents advantages and challenges, and the optimal choice depends on the type and complexity of the available data.

This section also analyzes the limitations and applicability of each algorithm, contributing to the development of a solid theoretical framework for efficient energy management.

To compare the prediction accuracy of each algorithm, the following calculation assumptions were considered:

- applying the algorithms to the same dataset,
- monitoring a single electrical circuit,
- using the same time interval for the analyzed data.

4.2. Machine learning techniques for predictive optimization

Machine learning (ML) involves deriving an action or a result from observations or data inputs. Conceptually, ML functions as a complex mathematical formula that processes inputs to generate results through learned models. Training an ML model involves identifying the optimal formula for specific input-output pairs and the analyzed dataset.

The list of algorithms is presented in ascending order according to their complexity and computational power requirements. Each description includes the algorithm's methodology and its relevance for predicting measured values in integrated energy management systems.

Linear regression

Linear regression is based on a direct correlation between an output variable and one or more input variables, making it suitable for estimating parameters such as energy consumption or voltage using a set of predictive factors.

ARIMA models

ARIMA integrates autoregression (AR), integrated differencing (I), and moving average (MA) to model and analyze time series data. It is useful for predicting sequential data in electrical networks, such as future load forecasts or energy demand.

LSTM Neural Networks

LSTM models are an extension of recurrent neural networks (RNNs), designed to mitigate the vanishing gradient problem and efficiently model relationships between data over extended periods.

By leveraging these advanced machine learning algorithms, the proposed energy monitoring solution can offer a comprehensive and efficient approach to energy management in buildings, improving and optimizing energy use across the POLITEHNICA University of Bucharest campus. Comparison will allow for the identification of the most efficient method for predicting measured values in electrical networks, ensuring efficient management of energy resources. Data processing for anomaly elimination and measurement error correction is essential to ensure accuracy and reliability in predictions.

5. Demand-Side Management (DSM) Programs

This chapter introduces and presents the theoretical and practical concepts related to Demand-Side Management (DSM) programs, which aim to optimize energy consumption by involving both end users and energy providers.

5.1. Theoretical considerations regarding DSM programs

This subsection presents the fundamental concepts of demand-side management (DSM) programs, highlighting their role in influencing energy consumption. Additionally, the economic and energy impact of implementing these programs is discussed, emphasizing their benefits for both consumers and providers.

DSM programs can serve as an alternative solution to expanding energy infrastructure for generation, transmission, distribution, and supply, while also offering an opportunity for businesses in the energy efficiency sector. DSM focuses on the more efficient use of energy, requiring significantly lower costs compared to increasing generation and distribution capacities.

Energy efficiency concerns can be initiated either individually by consumers or at a broader level through national programs or government initiatives.

DSM can be applied in a variety of ways, including:

- reducing peak loads through demand management,
- optimizing consumption by filling load gaps,
- shifting energy demand during peak hours,
- strategically conserving energy, particularly at the level of the National Energy System (SEN),
- promoting increased electricity consumption in transport as an alternative to fossil fuels. [5]

5.2. Effects of DSM programs on energy consumption management

This subsection analyzes the effects of implementing DSM programs on energy consumption management. These programs aim to optimize energy use by influencing demand from both consumers and suppliers.

By applying specific efficiency strategies, DSM programs contribute to reducing peak loads, redistributing consumption, and conserving energy resources, all of which have a direct impact on energy and economic performance.

DSM programs are targeted at specific consumer segments or at removing barriers to efficient energy use. Special attention is given to initiatives that promote behavioral changes among residential consumers, as well as to partnerships between suppliers, governments, and Energy Service Companies (ESCOs) to implement comprehensive energy efficiency programs.

Cost and tariff control becomes possible when suppliers can adjust energy demand based on available resources. The Day-Ahead Market (PZU) prices play an essential role in transmitting economic signals to consumers, influencing demand. The main goal of DSM programs is to improve the supplier-consumer relationship, generating mutual benefits.

For energy providers, the advantages include:

- reducing the primary resources needed in power plants,
- postponing investments in new generation capacities,
- minimizing energy losses in transmission and distribution networks,
- delaying energy infrastructure expansion.
- For consumers, DSM leads to:
- increased energy efficiency,
- achieving the same end-use energy output with lower consumption,
- reducing energy costs by lowering demand.

Implementation of DSM programs in university campuses

The successful implementation of energy management programs requires regulations and incentives from authorities. Figure 5.1 presents a model for DSM implementation. [5]

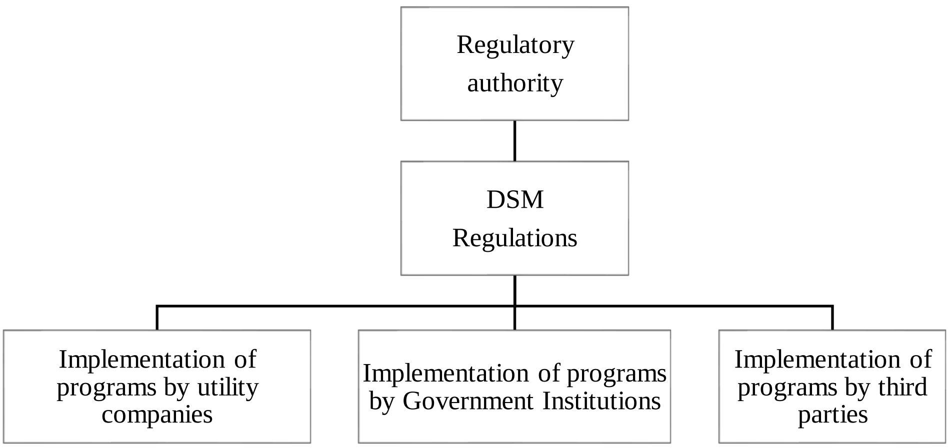

Figure 5.1 *DSM implementation model*

6. Validation of Research Results in Implemented Applications within the POLITEHNICA University of Bucharest Campus

This chapter presents the validation of research results and simulations for integrated energy management solutions, focusing on implementations carried out within the POLITEHNICA University of Bucharest campus. It details the development and implementation processes of real-time energy flow monitoring and control solutions, including the validation of the solution for the Passive House, as well as the Campus and Precis buildings within the university.

6.1. Development and implementation of solutions in the POLITEHNICA University of Bucharest campus

In this subsection, the implementation of the integrated energy management system in the POLITEHNICA University of Bucharest campus is presented, structured according to the main stages of the proposed methodology.

Stage 1: Identifying Consumers and Configuring Monitoring

In the first stage, the buildings and electrical circuits requiring detailed monitoring were identified. The CAMPUS and PRECIS buildings were selected for the initial implementation of the solution.

Within these buildings, energy analyzers were installed on each phase of the electrical circuits, monitoring:

- Voltage and current intensity
- Power factor
- Current and voltage harmonics

Stage 2: Defining the System Topology and Architecture

After installing the energy analyzers, the network topology was defined, including communication channels and utilized protocols. The collected data is initially transmitted via the Modbus protocol to aggregation PLCs, which then forward it to the central node using MQTT and TCP/IP protocols. This architecture ensures fast and secure communication between the measuring equipment and the central server, facilitating real-time data integration and analysis.

Stage 3: Implementing the Data Management and Visualization System

An essential step in this stage was the installation and configuration of the central node in the Passive House, which supports the entire data storage, monitoring, and processing infrastructure. The central node consists of server equipment that collects data from the devices installed in the CAMPUS and PRECIS buildings.

Stage 4: Implementing Prediction Algorithms for Energy Consumption Optimization

To enhance energy efficiency, prediction algorithms were tested and implemented, based on real-time collected data. Several models were analyzed, with ARIMA and LSTM proving to be the most effective in forecasting energy consumption. By integrating these algorithms, the system provides reliable forecasts, enabling energy consumption adjustments based on identified trends.

Stage 5: Implementing Energy Efficiency Solutions

In the final stage, solutions for optimizing consumption and improving energy efficiency within the POLITEHNICA University of Bucharest campus were studied. These solutions include: DSM programs, Automation, Load balancing, Power quality improvement measures.

6.2. Architecture of the integrated energy management system - POLITEHNICA University of Bucharest

The proposed network follows a star topology integration. Data is collected from sensors and energy analyzers using specific communication protocols (Modbus for analyzers and MQTT for solar radiation and temperature sensors, as well as data transmission between sites using MQTT over TCP/IP).

All data is transmitted to a central server, which manages storage and processing using an ESXi hypervisor, running multiple virtual machines configured with the required roles.

This setup provides both redundancy and scalability, ensuring that data collected from various IoT devices is transmitted and processed efficiently and securely. Redundancy in this network refers to multiple communication paths and backup mechanisms for each network node, minimizing the risk of data loss in the event of a failure. Scalability enables network expansion by adding new devices or sensors without impacting overall system performance.

As new IoT devices are added, the network can handle the increased data volume by using efficient communication protocols and powerful central servers, which can distribute processing and data storage tasks. Additionally, the modular configuration of the network allows for the easy integration of new technologies and equipment, ensuring their compatibility and interoperability with the existing infrastructure.

Figure 6.1 provides a detailed view of the connections and data flow in the remote site monitoring solution.

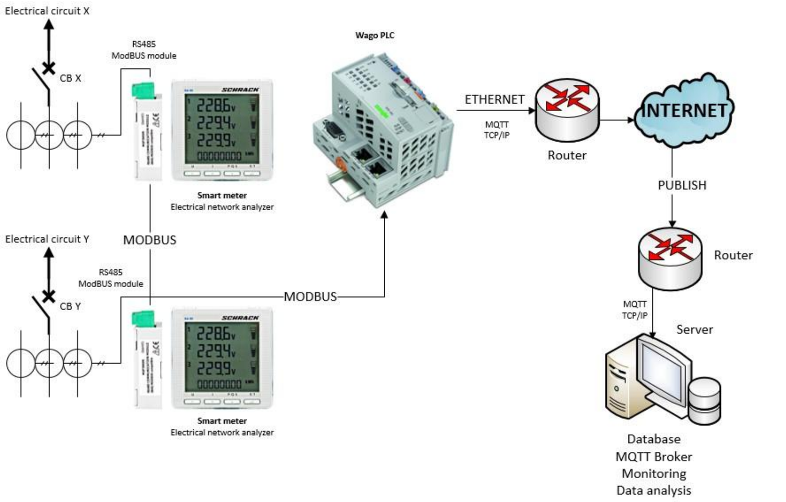

Figure 6.1 *Detailed Remote Site Monitoring Solution*

The proposed solution focuses on implementing an integrated monitoring system for electrical circuits within the university campus, covering both major energy consumers such as HVAC systems and smaller distributed consumers across the network.

As part of the integrated energy management solution implementation, network analyzers, current/voltage transformers, and a PLC aggregator were installed in the main electrical panel of the CAMPUS and PRECIS buildings.

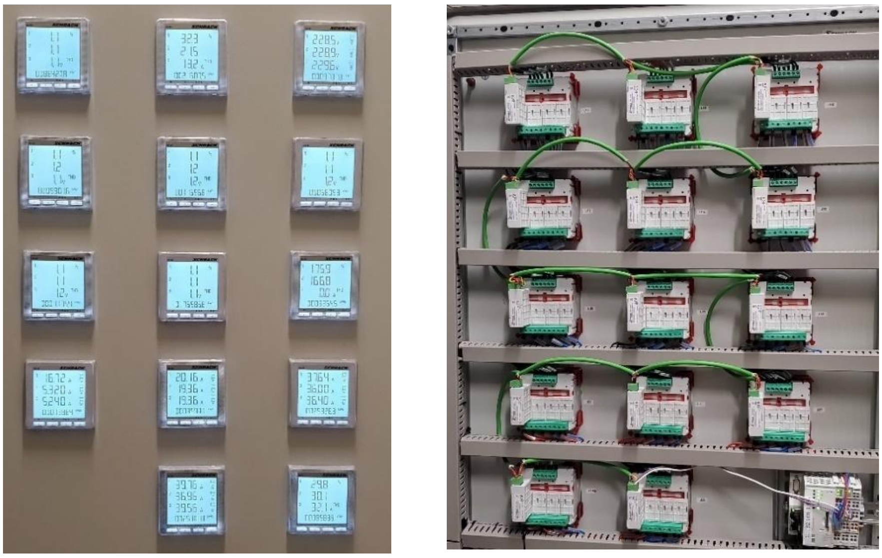

Figure 6.2 *Main Electrical Panel of the CAMPUS Building*

Figure 6.3 *Installation of Current Transformers*

The network architecture of the integrated energy monitoring system is designed to provide a scalable and efficient environment for data storage and processing. It facilitates communication between various system components, including smart meters, programmable logic controllers (PLCs), a central server, and an advanced analytics platform.

Figure 6.4 illustrates the proposed architecture for the technical virtualization solution of the IT infrastructure.

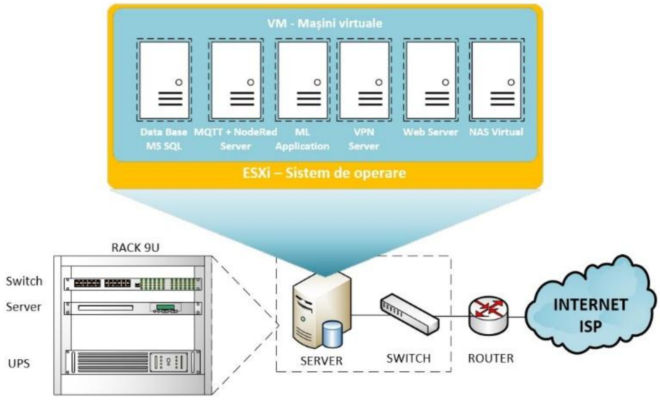

Figure 6.4 *Current Network Architecture for Integrated Energy Management*

To complement the network architecture, Figure 6.5 presents the logical flow of machine learning algorithm implementation within the monitoring system. This diagram provides a clear view of data collection, processing, and analysis processes, emphasizing how predictive models are used to forecast energy consumption.

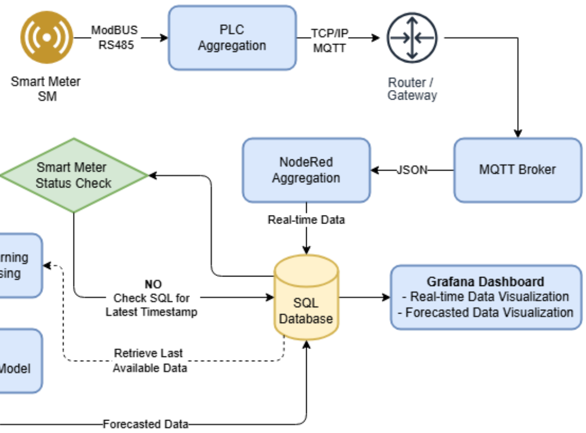

Figure 6.5 *Logical Flow Diagram – Machine Learning Algorithms*

For a better understanding of the practical application of the system, Figure 6.6 illustrates the implementation of the sensor and IoT device network in the POLITEHNICA University of Bucharest campus.

This solution enables the optimization of energy usage through a centralized, scalable, and flexible system. The integration of IoT technologies and virtualized infrastructure ensures an efficient platform for energy resource management, facilitating the implementation of advanced strategies for reducing consumption and optimizing the efficiency of the integrated energy system.

Figure 6.6 *Real-Time and Forecasted Data Visualization*

7. Conclusions and Perspectives for Research Development

The conclusion chapter provides a summary of the entire thesis, highlighting the obtained results, original contributions to the field of energy management, and analyzing the impact of the conducted research.

7.1. Obtained results

This subsection presents fundamental conclusions and technical and economic analyses conducted throughout the integrated energy management project.

Optimization of the Supplier-User Relationship through DSM

The integration of DSM programs allowed for better consumption management without the need for real-time adjustments based on energy market prices. The implementation of the solution improved consumption visibility, enabled the adaptation of energy usage strategies, and supported data-driven operational decisions.

Economic Viability

The technical-economic analysis demonstrated that the implemented system is viable and profitable. The Net Present Value (NPV) was positive, confirming that the financial benefits resulting from energy savings exceed the investment costs. The Internal Rate of Return (IRR) exceeded the discount rate, indicating a profitable project, while the Payback Period (PP) was within the acceptable limit, showing that the implementation will be amortized within a relatively short timeframe.

Environmental Impact

The automation and optimization of energy consumption contributed to a reduction in CO_2 emissions by 23.3 tons per year, equivalent to 8.9 tons of oil equivalent (toe) savings. This result highlights the positive impact on campus sustainability and supports energy efficiency objectives.

Clear Methodology and Scalability

The project provided a clear methodology for developing an integrated energy management system, consolidating a scalable model ready for expansion. The high granularity of measurements and the accuracy of the collected data allow for the rapid identification of imbalances and real-time resource optimization.

Performance of Prediction Algorithms

The comparison of energy consumption prediction models demonstrated that ARIMA represents the optimal solution in terms of the accuracy-to-hardware resources ratio, maintaining an average error below 5% under normal consumption conditions.

Although the LSTM model has a high capacity for capturing complex patterns and seasonality, its computational requirements made its implementation less efficient within the current infrastructure.

Linear regression was analyzed as a baseline model, but its limitations in modeling complex variations and seasonality resulted in significant errors, exceeding 10-15% in some cases.

Technical Architecture of the System

The solution was implemented using a virtualized infrastructure, based on a central ESXi server, which allows service segmentation and efficient resource management. This approach provided scalability, reduced hardware costs, and more flexible administration of data flows. The system allows for the easy integration of new measurement points and the expansion of processing capabilities without major structural modifications.

In conclusion, the implementation of the system demonstrated the feasibility of using advanced technologies for optimizing energy consumption, bringing direct benefits to operational, economic, and environmental efficiency. The obtained results support the expansion of the system by adding new predictive analysis modules, as well as integrating advanced automation and control mechanisms, thus strengthening the efficiency and sustainability of the energy infrastructure.

7.2. Original contributions

The implementation and development of an integrated energy management system have brought significant original contributions, both from the perspective of the proposed methodology and the applied technical solutions. These contributions focus on creating a scalable and replicable framework for optimizing energy consumption through the use of IoT technologies, virtualized infrastructure, and predictive algorithms.

Establishing a methodology for implementing the integrated energy management system

A fundamental contribution of this work consists in the development of a structured methodology for implementing an integrated energy management system. The proposed methodology includes identifying optimization needs for energy consumption, defining the system topology, establishing the network architecture, and integrating a central node for data processing.

This process concludes with monitoring, analyzing, and visualizing data, ensuring advanced security and infrastructure protection against cyber-attacks. An innovative component of the methodology is the integration of predictive algorithms, which enable consumption optimization by anticipating energy needs and adjusting resource usage accordingly.

Practical Applications of Integrated Energy Management in the POLITEHNICA University of Bucharest Campus

A novelty element is the practical application of the energy monitoring system within the POLITEHNICA University of Bucharest campus, a real environment with complex requirements. The implementation of this system enables granular data collection and analysis, as well as resource optimization by identifying and correcting inefficiencies. POLITEHNICA University of Bucharest thus becomes an example of the digital transformation of energy infrastructure, with economic and sustainability benefits.

Integration of a central virtualization-based node for service segmentation

Another major contribution is the use of virtualization technologies for developing a central node capable of efficiently segmenting system services. Type 1 hypervisor-based virtualization allows for the dynamic allocation of hardware resources and the isolation of critical services (monitoring, analysis, security), thereby optimizing the reliability, flexibility, and performance of the system.

This solution offers high scalability, facilitating infrastructure expansion without requiring significant additional investments.

Testing and optimizing predictive algorithms for energy consumption

This study contributes through a comparative analysis of advanced energy prediction algorithms, such as ARIMA, LSTM, and linear regression. Various parameter sets were tested and adjusted for each algorithm, leading to the validation of ARIMA as the optimal model for the current infrastructure due to its favorable accuracy-to-hardware requirements ratio.

This contribution is essential for the development of efficient predictive strategies, capable of improving real-time energy management.

Evaluation of the impact of cybersecurity measures in energy management networks

An innovative aspect of the research is the integration and evaluation of advanced cybersecurity measures in energy management systems. The implementation of data encryption, the use of secure protocols, and the adoption of restricted access policies ensure the protection of infrastructure against attacks. This contribution is essential in the context of the increasing security risks associated with IoT devices and smart grids.

Development of a replicable model for other institutions

A significant outcome of this solution is the creation of a standardized implementation model for an integrated energy management system, based on the experience of POLITEHNICA University of Bucharest. This model can be replicated and adapted in other public and private institutions, providing a scalable and sustainable solution for energy consumption optimization. Thus, the original contribution of this thesis extends beyond local implementation, offering a framework that can support the transition toward smart buildings at both national and international levels.

These original contributions emphasize the innovative nature of the thesis, demonstrating the practical applicability of the proposed solutions and the positive impact of modern technologies on efficient energy management.

7.3. Scientific Publications

This subsection presents the scientific papers published and those in progress or under review, resulting from the doctoral research activities. These papers focus on the implementation and development of an integrated energy monitoring and management system using IoT and IoE technologies.

List of Published Articles:

- **Enhancing Monitoring and Control of an HVAC System through IoT**, Vladimir Tanasiev, Stefanita Pluteanu, Horia Necula, Roxana Patrascu, January 2022, Energies 15(3):924, DOI:10.3390/en15030924, WOS:000760148100001.
- **Renewable Energy Production in Decommissioned Power Plant Sites for Sustainable Cities-The Case Study of Romania,** Adrian Ciocănea, Mircea Scripcariu, Ştefăniţă Pluteanu, Bogdan Tofan, Conference paper 20 September 2020, Part of the Springer Proceedings in Energy book series (SPE), DOI:10.1007/978-3-030-55757-7_19.
- **Integration of BIM Solutions and IoT in Smart Houses,** Gabriela Nicoleta Sava, Stefanita Pluteanu, Vladimir Tanasiev, Roxana Patrascu, Horia Necula, 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), DOI:10.1109/EEEIC.2018.8494628, WOS:000450163703058.
- **Demand-side Management Programs – A joint environmental protection action. Case study: The lighting system in the Campus of the University POLITEHNICA of Bucharest,** Mircea Scripcariu, Ioan Sevastian Bitir-Istrate, Cristian Gheorghiu, Ştefăniţă Pluteanu, Aida Maria Neniu, E3S Web of Conferences 112, 04006 (2019), 8th International Conference on Thermal Equipment, Renewable Energy and Rural Development (TE-RE-RD 2019), DOI:10.1051/e3sconf/201911204006, WOS:000619989000073.
- **Offshore Wind Power Plant and Electrical Network Development: Romanian Case Study,** Mircea Scripcariu, Gabriela Nicoleta SAVA, Stefanita Pluteanu, Oana Udrea, JOURNAL OF ENERGY ENGINEERING, Volume: 144, Issue: 2, APR 2018, (IF 1,632), ISI Web of Science, DOI:10.1061/(ASCE)EY.1943-7897.0000511, WOS:000425610500003.

List of Articles in Progress and Under Preparation:

- **Regulatory and Economic Impacts of BIM Implementation in the Construction Industry**, Ștefăniță PLUTEANU, Gabriela Nicoleta TANASIEV, Roxana PĂTRAȘCU, Vladimir TANASIEV – Buletin Științific Universitatea Politehnica București, Submission ID: 15514
- **Enhancing environmental preservation of the Danube Delta Biosphere Reserve through IoT custom-built monitoring station and Artificial Intelligence**, Vladimir TANASIEV, Tudor PRISECARU, Vasilica STEFAN, Emil TUDOR, Stefanita PLUTEANU, Roxana PATRASCU, Remote Sensing of Environment, 2023 – under review

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