POLITEHNICA UNIVERSITY
OF BUCHAREST

Doctoral School of Electronics, Telecommunications and Information Technology

Decision No. ____ from DD-MM-YYYY

Ph.D. THESIS SUMMARY

Maria Simona RABOACA

CONTRIBUȚII LA OPTIMIZAREA ȘI TESTAREA SISTEMELOR ENERGETICE ÎN TIMP REAL

CONTRIBUTIONS TO THE OPTIMIZATION AND REAL-TIME TESTING OF POWER SYSTEMS

THESIS COMMITTEE

Prof. Dr. Ing. Gheorghe BREZEANU Politehnica Univ. of Bucharest	President
Prof. Dr. Ing. Nicu Bizon Politehnica Univ. of Bucharest	PhD Supervisor
Prof. Dr. Ing. Dorin Marius PETREUŞ Univ. Tech. of Cluj-Napoca	Referee
Prof. Dr. Ing. Horia Leonard ANDREI Univ. of Valahia Târgoviște	Referee
Dr. Ing. Constantin RĂDOI Politehnica Univ. of Bucharest	Referee

BUCHAREST 2025

Content

Chapter 1

Introduction

The development of the national energy sector, planned for the period 2025–2035 and projected through 2050, is outlined in the strategic document titled “Romania’s Energy Strategy (RES) 2025–2035, with a 2050 Outlook”. This strategy sets forth the medium- and long-term vision for the energy sector, outlining the strategic objectives and key directions of action. The modernization of the energy system is an absolute imperative in order to ensure sustainable economic development, enhance the competitiveness of the Romanian economy, improve quality of life, and support the transition to a sustainable energy model, in line with Romania’s environmental commitments at both European and international levels.

1.1 Presentation of the field of the doctoral thesis

The present doctoral thesis falls within the field of Electronic Engineering, Telecommunications, and Information Technologies, focusing on the real-time optimization and testing of energy systems in the context of the transition toward a decarbonized and sustainable energy sector. In this regard, green hydrogen technology represents a fundamental component of the future energy architecture, serving as a strategic energy vector for reducing greenhouse gas emissions and enhancing the operational flexibility of complex energy systems.

The integration of real-time data acquisition and digitalization, together with the optimization of energy systems incorporating green hydrogen, enables a predictive approach to the energy transition process.

In order to effectively assess and integrate green hydrogen-based technologies, the simulation of energy systems plays a pivotal role. Tools such as MATLAB/Simulink [8], TRNSYS [9], iHOGA [10], and OpenModelica [11] enable the dynamic modeling of hybrid network behavior, optimal sizing of equipment, as well as cost-benefit analysis under various operational scenarios.

1.2 Scope of the doctoral thesis

The objective of this doctoral thesis is to develop an integrated methodological framework for the real-time optimization and testing of energy systems that incorporate green hydrogen, with a focus on the acquisition and analysis of data from renewable energy sources. Specifically, the research aims to simulate and assess the energy and economic performance of investments in new electricity generation capacities from renewable sources, covering the entire technological chain—from production to storage and utilization of green hydrogen.

This research seeks to contribute both methodologically and practically to the modernization of energy infrastructure through the acquisition, processing, and interpretation of real-time operational data. Particular attention is given to the integration of green hydrogen-based technologies in support of decarbonization goals, energy efficiency, and the transition toward an intelligent, flexible, and sustainable energy system.

1.3 Content of the doctoral thesis

The doctoral thesis aims to provide an integrated approach to the real-time optimization and testing of energy systems, with a focus on the integration of renewable energy sources and green hydrogen-based technologies. The work is organized into seven main chapters, each contributing step by step to the theoretical foundation, methodological framework, and practical contributions of the research.

Chapter 1 – Introduction

This chapter presents the strategic context of the national and European energy transition, highlighting the role of renewable energy sources and innovative technologies such as green hydrogen in reducing carbon emissions and achieving sustainability goals. It also emphasizes the importance of digitalization and real-time data acquisition for monitoring, control, and optimization of energy systems, which supports infrastructure modernization and the development of smart, flexible, and efficient networks in line with decarbonization objectives.

Chapter 2 – State of the Art in Real-Time Testing

This chapter reviews the current state of knowledge and applications in the field of real-time testing and digital simulation, focusing on the techniques and platforms used for validating complex systems. It introduces the concept of real-time simulation, differentiating between fully digital simulations and Hardware-in-the-Loop (HIL) simulations, and discusses the advantages and applicability of the OPAL-RT platform, particularly the OP5600 system, across various industrial domains.

Chapter 3 – Design and Implementation of Energy Systems

Chapter 3 addresses the design and implementation of energy systems, emphasizing strategies for the development of smart and efficient infrastructure tailored to the management of renewable resources and advanced energy storage technologies. The importance of adopting integrated technological solutions based on advanced digital platforms, such as OPAL-RT, and real-time monitoring systems is highlighted. These technologies enable continuous data collection and processing, dynamic optimization and control strategies, improved equipment performance, reduced losses, and extended infrastructure lifespan under safe and reliable operating conditions.

Chapter 4 – Optimization and Simulation of Energy Systems

This chapter investigates the technical and economic performance of a green hydrogen production system powered by wind energy, through the simulation and comparison of four distinct operational scenarios. Each scenario reflects a different strategy for using the available energy and adapting production capacity to real-time resource conditions.

Chapter 5 – Performance Indicators

Chapter 5 presents an in-depth comparative evaluation of the four operational scenarios for the green hydrogen production system based on wind energy. The analysis focuses on identifying annual energy and economic performance using a set of relevant techno-economic indicators, summarized in comparative tables and graphs.

Based on parameters such as energy used, hydrogen produced, module utilization rate, water consumption, revenues, expenses, and net profit, Scenario 3 was identified as offering the best balance between technical efficiency, sustainability, and economic viability. It nearly fully exploits renewable energy without relying on the national grid, while maintaining high production and revenue levels at relatively low costs.

Chapter 6 – Real-Time Data Acquisition Platform
Chapter 6 describes and experimentally validates integrated digital platforms for real-time monitoring and data analysis, applied to a functional photovoltaic system implemented in a laboratory environment. The chapter's main objective is to investigate data acquisition and storage architectures from heterogeneous sources (PV panels, environmental sensors, storage systems, inverter) in order to evaluate system performance, autonomous operation capacity, and integration potential into smart energy grids.
Three distinct software platforms, generically named Test 1, Test 2, and Test 3, were developed and tested—each addressing specific functional requirements related to the collection, synchronization, and interpretation of relevant data.
The chapter confirms the hypothesis that integrating IoT, blockchain, and real-time analytics technologies can significantly enhance the processes of evaluation, control, and optimization of renewable-based energy systems. The results support the foundation of advanced smart energy management models capable of enabling the transition to a sustainable and digitalized economy.
Chapter 7 – Conclusions
This final chapter synthesizes the results obtained, highlighting the added value of the research in the field. It proposes future directions for scientific exploration, taking into account the accelerating pace of the energy transition and the need for scalable, efficient, and sustainable solutions. The chapter also outlines the author's original scientific contributions.

Chapter 2

Current State of Knowledge on Real-Time Testing

Real-time digital simulation has the capability to replicate a real system. The actual system is mirrored and generates the necessary control signals.
Due to their high reliability and performance, **OPAL-RT simulators** [12] are technically viable and readily available. The OPAL-RT simulator includes the following digital simulation programs: **eFPGAsim** [13], **ePHASORSIM** [14], **eMEGAsim** [15], and **HYPERSIM** [16].
eMEGAsim is a scalable and flexible real-time digital simulation program that includes **RTE Event**, **ARTEMIS**, and **RT-LAB** software.

2.1 OPAL-RT Interface and the Connection Between RT-Lab and MATLAB/Simulink

The OPAL-RT interface is associated with **RT-Lab software**, which is based on MATLAB/Simulink's **SimPowerSystems**.

The main feature of this software is its ability to meet transient simulation requirements for electromechanical drives and electrical systems.

2.2 SIL/HIL Challenges and Solutions Used in the Thesis

Hardware-in-the-loop (HIL) testing consists of real-time simulation by connecting real equipment and systems via sensors and actuators.
It enables users to perform realistic closed-loop tests without the need for testing on the actual physical system.
HIL refers to configurations involving low-power signal connections.

Chapter 3

Implementation and Design of Energy Systems

In the present doctoral thesis, the concept of **"real-time testing of energy systems"** is addressed, with the aim of identifying optimal solutions for testing and evaluating the performance of such systems. The focus is on developing efficient methods to support the users' energy consumption profiles, while integrating innovative technologies for energy production from renewable sources such as **solar and wind energy**, as well as **energy storage technologies**, particularly the use of **hydrogen**. This approach is specifically illustrated in **Figure 3.1**.

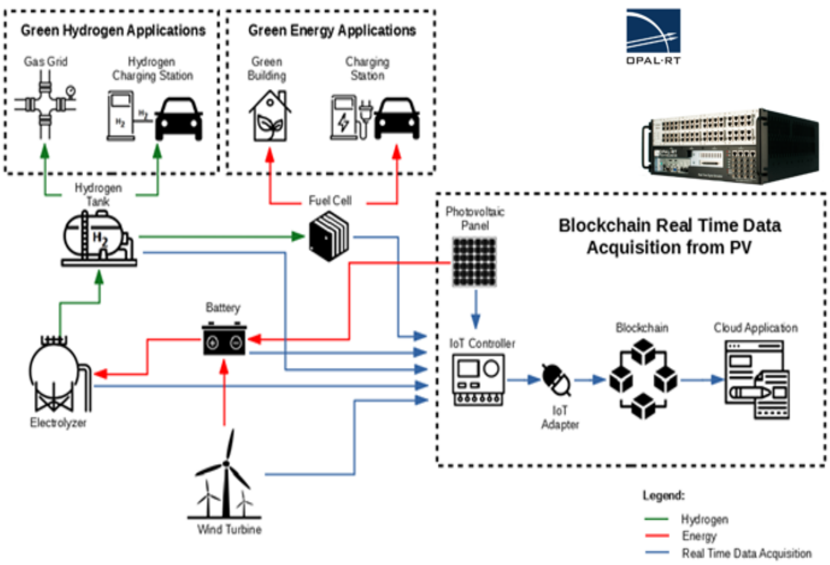

***Figure 3.1** – Concept of Real-Time Testing of Hybrid Energy Systems*

In **Figure 3.1**, an integrated architecture is presented, designed for the efficient management of energy resources derived from renewable sources and green hydrogen, as well as the process of real-time data collection and analysis for monitoring and optimizing the energy system.

3.1 Primary Energy Source Module

The **Primary Energy Source Module** is the main component responsible for the generation and supply of energy from renewable resources, such as photovoltaic panels, wind turbines, and other energy production technologies based on natural resources. This module is tasked with monitoring technical parameters such as power, voltage, current, and efficiency of energy sources, ensuring real-time data acquisition. Control and optimization strategies are also implemented at this level to maximize energy production and manage resource variability, thereby contributing to the overall stability and reliability of the energy system.

3.1.1 Wind Farm

The use of wind energy for electricity generation has a history of over a century, evolving from early windmills to today's technologically advanced wind generators. Within monitoring and control systems, key technical parameters—such as wind speed and direction, generated power, voltage, current, and turbine efficiency—are collected in real time to ensure optimized operation.

3.1.2 Photovoltaic Park

A photovoltaic park is an electricity generation infrastructure composed of a network of strategically mounted solar panels to maximize solar radiation capture under variable environmental conditions and to facilitate the direct conversion of solar energy into electricity. This investment contributes significantly to diversifying the national energy portfolio and reducing greenhouse gas emissions, being considered a fundamental pillar of the transition strategies toward a sustainable, low-emission economy.

3.1.3 Hydrogen – Energy Vector

Green hydrogen represents a highly promising energy vector, playing a crucial role in facilitating the transition to a sustainable energy system with reduced carbon emissions and diversified energy sources. This energy vector is produced through water electrolysis powered by renewable energy sources such as solar and wind, completely eliminating greenhouse gas emissions typically associated with conventional hydrogen production and use.

3.2 Consumer Module

The **Consumer Module** is a fundamental component in advanced energy management and control systems, responsible for monitoring, analyzing, and optimizing electricity usage within integrated energy systems. Its main function is the continuous, real-time collection of operational data from end-users and connected equipment, including electric vehicle charging stations, residential buildings, industrial and commercial units. This includes basic parameters such as energy consumption, temporal usage profiles, seasonal variations, voltage and current fluctuations, and other relevant technical indicators such as power factor, energy efficiency, and equipment operational status.

3.3 Storage Module

The **Storage Module** is a critical component of modern energy system infrastructure, with the primary objective of efficiently managing, monitoring, and controlling energy storage technologies, including battery systems, thermal storage solutions, and other advanced energy storage technologies. Its operation involves the continuous and real-time collection of operational and technical parameters, such as charging and discharging levels, conversion efficiency, and the degradation state of storage equipment.

3.3.1 Green Hydrogen Energy Storage Technology

Green hydrogen energy storage technology is an innovative and strategic component in the development of sustainable and efficient energy systems, with the potential to facilitate the large-scale integration of intermittent renewable sources, such as solar and wind energy, into modern energy grids.

Chapter 4

Optimization and Simulation of Energy Systems

4.1 Defining Optimization Objectives and Constraints for the Analyzed Scenarios

The main objective of Chapter 4 is to present, compare, and quantitatively evaluate the techno-economic performance resulting from the simulation of a hydrogen production system through electrolysis, under four distinct operational scenarios. This analysis aims to highlight the impact of electrolyzer operation modes on energy efficiency, economic sustainability, and the continuity of the hydrogen production process, under the specific conditions of integrating intermittent renewable resources (wind energy).

4.2 Electricity Production

To ensure accurate modeling of the production and storage capacity of the proposed energy system, it is necessary to preliminarily establish an estimated annual wind speed profile and the corresponding wind energy production. This step is essential for defining the operating scenarios of the electrolyzers and evaluating the loading level of the hydrogen storage units.

Over the course of one calendar year, the total estimated energy production of the wind farm is approximately **294,432 MWh**, based on the annual wind speed profile.

The monthly evolution of average hourly energy values is illustrated in Figure 4.2, offering an overview of seasonal wind potential variations and the energy availability for continuous electrolyzer operation. These parameters are fundamental for estimating the overall efficiency of the analyzed energy system and for determining the optimal operating regime for hydrogen production and storage facilities.

4.3 Scenario 1 – Proportional Operation in Adaptive Mode

In this scenario, all six electrolysis modules operate simultaneously at the same power level, adjusted proportionally to the available energy. The operating level is limited between **20% and 100% of nominal power (Pn)**. If the energy allocated per module drops below the minimum threshold of **20% (0.146 MWh/module)**, the entire electrolysis system is automatically shut down according to the manufacturer's technical specifications, to avoid accelerated wear and efficiency loss.

4.4 Scenario 2 – Uniform Operation at Minimum Admissible Power

In this case, all six modules operate continuously at the minimum power level, **20% of nominal capacity**, as long as at least **0.876 MWh** of total energy is available. This strategy aims to ensure continuous system operation with minimal energy consumption, avoiding frequent stops and restarts.

4.5 Scenario 3 – Selective Module Operation Based on Available Energy

This scenario involves activating a variable number of modules (**n < 6**) when total available energy is below **4.3 MW**. Modules are activated sequentially until reaching a consumption threshold of **0.876 MWh/module**. Inactive modules can be turned on only if they can individually receive more than **0.146 MWh** of energy. This ensures efficient and adaptive operation, avoiding grid overload and inefficient electrolyzer usage.

Scenario 3 proposes a flexible operational strategy based on sequential activation of electrolyzer modules according to available energy, limiting total consumption to **below 4.3 MW**. Modules are activated progressively up to **0.876 MWh/module**, and additional modules are only enabled if they can be allocated a minimum of **0.146 MWh/module**. This approach ensures efficient, adaptive operation, prevents overloading the electrical grid, and ensures operation only under optimal technical conditions.

The average hourly energy allocated to electrolyzer operation is **20,462 MWh/year**, reflecting a dynamically adapted operation regime based on wind energy availability. Throughout the year, all modules are used in a balanced manner, reflecting an effective rotation strategy that distributes wear evenly and increases system reliability.

The total hydrogen production in Scenario 3 was **4,428,740 Nm³** (equivalent to **394,718 kg**). The produced hydrogen was used according to the working hypothesis: **75% injected into the grid (3,321,555 Nm³)** and **25% sold in tankers (98,680 kg)**.

4.6 Scenario 4 – Continuous Operation at Nominal Capacity with External Grid Support

In this scenario, all six modules operate at nominal power (**0.876 MWh/module**) regardless of the wind energy production. Any energy shortfall is covered by purchasing electricity from the **National Energy System (SEN)** at a reference market price. This scenario ensures maximum operation of the electrolysis system, enabling assessment of the system's full capacity, though with significantly higher energy costs.

Comparison of Optimization Coefficients for the Analyzed Scenarios

To fully understand system performance under each scenario, a comparison of previously defined **optimization coefficients** is proposed. The summarized results are presented **in** Figure 4.4.

Table 4.4 *– Comparison of Optimization Coefficients for the Analyzed Scenarios*

Coefficient / Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
CUEA (Energy Use Efficiency Coefficient)	low	moderate	high	very high
CFO (Operational Flexibility Coefficient)	0	0.3	1	1
PS (System Performance)	medium	low	high	maximum
CAER (Renewable Energy Utilization Rate)	low	>80%	>95%	approx. 53%
CVEH (Hydrogen Economic Viability Coefficient)	<1	≈1	>2	>2.5

Chapter 5
Performance Indicators

5.1. Energy Performance Indicators – Scenario 1

The average annual values of the main energy performance parameters obtained in Scenario 1 are summarized in Table 5.1. From the analysis of these results, it is observed that under the technical specifications of the electrolyzer and the adopted working assumptions, the system operates for only ten months within a full calendar year.

5.2. Financial Performance Indicators – Scenario 1

The total revenue generated from the utilization of the hydrogen produced by the electrolysis installation, under Scenario 1, represents the sum of revenues obtained from the two main commercialization channels: (i) hydrogen injected into the natural gas grid and (ii) compressed hydrogen sold in tankers.

5.3. Energy Performance Indicators – Scenario 2

The average annual values of the energy performance parameters for Scenario 2 are presented in Table 5.3. The analysis of these data shows that, throughout the calendar year, the electrolysis system effectively operated for ten months, in accordance with the working hypotheses and the technical constraints specified in the equipment's datasheet.

5.4. Financial Performance Indicators – Scenario 2

The revenues generated from the hydrogen valorization in Scenario 2 comprise the sum of two main components: revenues from injecting hydrogen into the gas network and revenues from selling it in tankers. Table 5.4 summarizes the values corresponding to each of these financial indicators: Revenue – Hydrogen injected into the gas network, Revenue – Hydrogen sold in tankers, and Total Revenue – Hydrogen sold in Scenario 2. This structure enables a clear assessment of the contribution of each marketing channel to the overall economic performance of the analyzed scenario.

5.5. Energy Performance Indicators – Scenario 3

The average annual values of the main energy performance indicators obtained in Scenario 3 are shown in Table 5.5. It is observed that, over the calendar year, the electrolysis system operates continuously for 12 months, complying with both the technical conditions specified in the equipment datasheet and the operational assumptions made.

5.6. Financial Performance Indicators – Scenario 3

The revenue generated from the hydrogen produced in Scenario 3 consists of the total earnings from the two primary distribution channels: injection into the natural gas grid and delivery in compressed form via tankers.

5.7. Energy Performance Indicators – Scenario 4

The average annual energy performance values for Scenario 4 show that the electrolyzer operates for the entire 12-month period, in accordance with the technical requirements stated in the datasheet and in line with the working assumptions made in the study.

5.8. Financial Performance Indicators – Scenario 4

The total revenue generated from the valorization of hydrogen in Scenario 4 is determined by summing the revenues obtained from injecting into the gas network and from selling it in compressed form via tankers, as summarized in Table 5.8.

5.9. Sensitivity Analysis

For Scenarios 1, 2, 3, and 4, three critical variables were analyzed: (i) the cost of tap water, (ii) the price of hydrogen sold in tankers, and (iii) the price of hydrogen injected into the gas network. Additionally, for Scenario 4, an extra critical parameter was introduced: the price of electricity purchased from the National Energy System (SEN).

5.9.1. Sensitivity Analysis – Scenario 1

For the critical variable "tap water cost" (Figure 5.3), a 10% decrease in the discount rate results in a 0.0125% increase in Net Present Value (NPV) and a decrease in the Internal Rate of Return (IRR) to 0.42%. Conversely, a 10% increase in the discount rate causes a 0.0125% drop in NPV and an increase in IRR to 0.41%.

5.9.2. Sensitivity Analysis – Scenario 2

For the critical variable "tap water cost" (Figure 5.6), a 10% decrease in the discount rate leads to a 0.0041% increase in NPV and a decrease in IRR to 0.14%. Conversely, a 10% increase causes a 0.0041% decrease in NPV and an increase in IRR to 0.14%.

5.9.3. Sensitivity Analysis – Scenario 3

For the critical variable "tap water cost" (Figure 5.9), a 10% decrease in the discount rate results in a 0.0131% increase in NPV and a decrease in IRR to 0.43%. A 10% increase leads to a 0.0131% drop in NPV and an increase in IRR to 0.44%.

5.9.4. Sensitivity Analysis – Scenario 4

For the critical variable "tap water cost" (Figure 5.12), a 10% decrease in the discount rate causes a 0.0246% decrease in NPV and an increase in IRR to 0.81%. A 10% increase results in a 0.0246% increase in NPV and a decrease in IRR to 0.83%.

Chapter 6

Real-Time Data Acquisition Platform

6.1 Hardware and Software Architecture

The integrated and modular hardware-software architecture is presented in Figure 6.1, designed for real-time monitoring and control of energy systems. It supports the efficient management of renewable energy sources and energy storage technologies. At the center is the control and processing unit, visually represented by a Raspberry Pi board, which serves as the coordination and data analysis node for multiple peripheral components and field subsystems.

6.2 Experimental Stand Description

The system integrates photovoltaic panels made up of 26 standard-configuration modules, with an installed capacity of 8.58 kW. The energy storage units consist of batteries with a capacity of approximately 10 kWh. These are interconnected with the inverter, main controller, and energy management modules to ensure optimized operation of charging/discharging processes and energy flow management.

6.3 Hardware Equipment of the Experimental Stand

The photovoltaic system was installed on the rooftop of a building within ICSI. Figure 6.3 shows both the photovoltaic panels used for energy harvesting and the modern infrastructure of the building, highlighting the applicability of renewable energy solutions.

6.3.1 Photovoltaic Panel Field

A total of 25 photovoltaic panels were used for the construction of the experimental stand, distributed into two distinct categories.

6.3.2 Inverter

The inverter plays a central role in the functional architecture of photovoltaic systems, being essential in converting the electrical energy generated by the panels into usable form.

6.3.3 Battery

Four AGM-VRLA batteries were used in the experimental stand.

6.3.4 Consumer – Lighting System

The main energy consumer in the experimental stand is the building’s lighting system, designed to operate in a local supply mode, through the inverter and batteries.

6.3.5 Building Automation System

The automation system in the experimental stand plays a key role in managing energy flows and optimizing operation by coordinating between the inverter, power sources, distribution boards, and end-users.

6.3.6 Rooftop Automation System

Figure 6.10 shows Automation Panel 2, a key element of the automation infrastructure, located near the photovoltaic field, directly on the building's rooftop.

6.3.7 Block Diagram of the Experimental Stand

The energy generated as direct current (DC) is directed to a multifunctional inverter, which converts it into alternating current (AC), compatible with the building's electrical loads and the public grid.

6.4 Hardware Equipment for Data Acquisition

The experimental stand uses a series of Internet of Things (IoT) devices, whose role is to monitor and transmit, in real time, relevant parameters for evaluating the performance of the photovoltaic system.

6.5 Experimental Results

Intermediate results are illustrated, generated by two distinct microservices developed for the collection and processing of specific sets of operational data.

6.5.1 Centralization of Collected Data

In the experimental stand, data from various sources – photovoltaic panels, hybrid inverter, batteries, temperature sensors, solar radiation sensors (pyranometer), solar trackers (Solys2), and various consumers – are continuously, asynchronously, and heterogeneously collected.

6.5.2 Test 1 Platform

The results generated by the software application "Test 1 Platform," called "Energy Calculator for CNHPC," dedicated to monitoring green energy production, are presented.

6.5.3 Test 2 Platform

The application called "Test 2 Platform" was developed for real-time acquisition and analysis of data from the photovoltaic system in the experimental stand, for the continuous evaluation of energy performance. During the research, the application was used to monitor data collected from September 2–6, 2022, corresponding to a four-day period of continuous system operation.

6.5.4 Test 3 Platform

In the third experimental stage of the monitoring platform, "Test 3 Platform," a real-time data acquisition and visualization system was implemented to analyze the operational behavior of the photovoltaic panels under real environmental conditions.

6.6 Analysis of Obtained Results

This section presents the analysis of the results from the three tests.

Chapter 7

Conclusions

This doctoral thesis has undertaken an integrated approach to the design, simulation, optimization, and validation of energy systems, with a particular focus on green hydrogen production powered by renewable sources, especially wind energy. The central objective of the research was to identify a robust, flexible, and sustainable techno-economic model capable of addressing current demands for decarbonization, energy autonomy, and operational efficiency.

Firstly, by contextualizing the energy transition at both national and European levels, the thesis substantiated the necessity of integrating green hydrogen as a strategic vector within the energy mix, supported by digitalization, IoT, and advanced real-time monitoring and control solutions. Secondly, the thesis demonstrated the viability of real-time simulation technologies (SIL, HIL) using the OPAL-RT platform, providing a coherent methodological framework for the development, testing, and validation of energy control systems under realistic and reproducible conditions. This approach allows for the reduction of risks, costs, and development time for innovative energy solutions.

Subsequently, a modular electrolysis system powered by wind resources was designed and integrated into an experimental platform capable of adaptive testing and operation. Through the simulation of four distinct operational scenarios, Scenario 3 emerged as the most advantageous—characterized by maximum flexibility, full energy autonomy, and a progressive module activation strategy. This scenario offered the best balance between technical performance, economic profitability, and sustainability.

The major scientific contribution lies in the development and application of a set of optimization coefficients (CUEA, CFO, CAER, CVEH), which enable a quantitative and comparative evaluation of the performance of the analyzed scenarios. Moreover, the sensitivity analysis applied to critical variables validated the robustness of the proposed model, demonstrating that moderate variations in economic parameters do not compromise the investment's viability..

7.1 Obtained results

Results Obtained – Chapter 2

The results obtained in Chapter 2 highlight that the OPAL-RT platform, particularly the OP5600 model, is a reliable and versatile solution for real-time simulation of energy and control systems, successfully used in both industrial and academic settings. It was demonstrated that the interfacing and synchronization between the OPAL-RT platform and the MATLAB/Simulink environments is efficient, facilitating the development and automated testing of controllers, significantly reducing processing time and increasing verification accuracy. The coherent transition between Model-in-the-Loop (MIL), Software-in-the-Loop (SIL), and Hardware-in-the-Loop (HIL) stages ensures continuity and consistency of the control logic, eliminating the need for model duplication and facilitating the evolution of systems from research to practical implementation. Moreover, the use of automated verification methodologies and centralized management of multiple models had a positive impact on development process reliability, reducing human error risks and improving data consistency. Consequently, these fundamental results support the systematic adoption of real-time digital simulation as an essential methodology for designing, validating, and optimizing modern energy systems, offering direct benefits for domains such as renewable sources, energy storage, and advanced grid control, and contributing to advancing technical knowledge in the field.

Results Obtained – Chapter 3

The results obtained in Chapter 3 demonstrate that implementing and designing modern energy systems based on advanced digital technologies, such as OPAL-RT platforms and real-time data acquisition systems, lead to efficient, safe, and sustainable energy resource management. It was shown that using specialized modules for testing and validating systems under real operating conditions allows for early identification of deficiencies, reduction of operational risks, and extension of equipment lifespan, thus enhancing infrastructure reliability.

Additionally, the benefits of developing energy storage infrastructure, particularly through technologies such as electrolysis for green hydrogen, efficient storage and transport systems, were emphasized as strategic solutions for balancing energy flows from intermittent renewable sources. Furthermore, the research confirmed that holistic approaches integrated into digital solutions ensure flexibility, adaptability, and sustainability, contributing to greenhouse gas emissions reduction and increased energy system resilience in the context of a transition toward a verifiably sustainable and environmentally responsible economy.

Results Obtained – Chapter 4

Chapter 4 focused on a comparative analysis of four operational scenarios for a modular electrolysis system powered by renewable energy, mainly wind. The main objective was to determine the operational configuration that ensures optimal balance between energy efficiency, economic profitability, and technological sustainability.

The results revealed significant differences between the four scenarios:

- **Scenario 1** assumed full-capacity operation (4.3 MW), leading to limited annual operating hours and low hydrogen output. Economic indicators were weak, and resource utilization and profitability coefficients were low.
- **Scenario 2** allowed system activation at a minimum threshold of 1.45 MW. Hydrogen production increased compared to Scenario 1, but remained low during periods of low energy availability. Economic performance improved but was still insufficient for significant profitability.
- **Scenario 3**, featuring progressive and flexible module operation (sequential activation based on available energy), yielded the most balanced outcomes. Total annual energy consumption was 20,462 MWh, hydrogen production reached 394,718 kg, and net annual profit was €401,871. The system operated entirely on wind energy, achieving a renewable energy coverage coefficient of over 95%. The optimization coefficients (CFO = 1, CVEH > 2) confirmed this scenario's superiority in terms of flexibility and profitability.
- **Scenario 4** involved continuous nominal-capacity operation with supplementary energy from the national grid (SEN). Although it achieved the highest hydrogen production (740,150 kg) and the highest absolute profit (€783,366), this was done with an annual energy consumption of 38,369 MWh, of which 17,806 MWh came from the SEN, resulting in over 46% dependency on the grid and a reduced energy autonomy coefficient (CAER ≈ 53%).

Thus, the analysis of optimization coefficients and economic indicators reveals Scenario 3 as the most efficient and sustainable operational strategy, optimizing renewable resource usage, minimizing SEN dependency, and maximizing profitability under flexible operation.

Results Obtained – Chapter 5

Chapter 5 aimed to provide a detailed comparative assessment of the techno-economic performance of the four proposed operating scenarios for a wind-powered green hydrogen production system. The analysis was conducted using relevant energy and financial performance indicators within a multi-criteria decision-making framework.

Key findings include:

- **Scenarios 1 and 2**, relying exclusively on local renewable sources, allowed operation for only 10 months per year. This limitation resulted in low annual hydrogen production volumes (381,268 kg in Scenario 1 and 123,358 kg in Scenario 2), leading to modest revenues and low profits. Despite full energy autonomy, their added economic value was limited.
- **Scenario 3** introduced a flexible operational strategy, where electrolyzer modules are activated progressively based on resource availability. This model enabled year-round operation without external energy sources (SEN), ensuring an annual hydrogen production of 394,718 kg and a net profit of €789,652. Notable performance metrics were recorded: CAER > 95%, CFO = 1, and CVEH > 2, positioning this scenario as a balanced option between sustainability, operational efficiency, and economic profitability.
- **Scenario 4** operated at nominal capacity year-round with significant SEN energy use (17,806 MWh). While it resulted in the highest operating costs (€703,688), it also achieved the highest hydrogen production (740,150 kg) and total revenue (€1,543,180), with a net profit similar to Scenario 3 (€783,366). However, its increased reliance on SEN reduced both autonomy and sustainability.

Based on the analyzed optimization coefficients (CAER, CFO, PS, CVEH, etc.), Scenario 3 demonstrated the best combined performance, favored for its balance of energy efficiency and financial viability.

Sensitivity analysis showed that ±10% variations in key variables (water cost, hydrogen sale price, SEN energy cost in Scenario 4) resulted in marginal changes in net present value (NPV), all below ±0.5%, underscoring the model's economic robustness. Graphical comparisons of NPV and internal rate of return (IRR) versus each critical variable confirmed overall system stability under moderate parametric variations. These findings support scalability and applicability under real-world conditions.

In conclusion, Chapter 5 rigorously demonstrated that Scenario 3 represents the optimal solution from the perspective of technological performance, energy sustainability, and economic viability for a wind-powered green hydrogen production system.

Results Obtained – Chapter 6

Chapter 6 yielded significant results regarding the design, implementation, and evaluation of an integrated energy monitoring and management system in a photovoltaic experimental setup using emerging technologies such as IoT, microservices, blockchain, and interactive web applications.

1. **Implementation of a digital infrastructure for energy acquisition and monitoring:** Three software applications (Test 1, Test 2, and Test 3) were developed and tested to capture real-time data from PV panels, batteries,

inverters, temperature, and solar radiation sensors. The data were asynchronously collected, cached, and transmitted to a distributed database (BigchainDB), ensuring traceability, consistency, and integrity.

2. **Green energy production assessment:** The "Test 1 platform" enabled analysis of monthly renewable energy production for August and September 2022. In August, the PV system generated 43.684 kWh (66.6% of consumption), and in September 110.571 kWh (58.5% of consumption). Despite absolute production growth, the percentage fell due to higher consumption, confirming the system's capacity to cover a significant portion of energy demand from green sources.
3. **Real-time operational parameter analysis:** Using the "Test 2 platform," detailed monitoring was performed between September 2–6, 2022, tracking consumed energy, grid energy, PV energy, and stored energy. Measurements included panel temperature, solar radiation, currents, and voltages, offering an integrated view of system performance under real conditions.
4. **Correlation of environmental parameters with PV performance:** The "Test 3 platform" enabled daily monitoring (October 12, 2021) of current, voltage, and panel temperature. The analysis revealed a direct influence of temperature and solar radiation on electrical parameters, with an inverse relationship between voltage and temperature, specific to solar cell behavior. Peak current and voltage aligned with solar intensity around midday.
5. **Integration of energy data into blockchain:** A major achievement of this chapter was the use of blockchain technology for secure, distributed energy data storage. This model ensures record immutability, supporting auditing, comparative analysis, and predictive modeling in scientific and industrial contexts. This approach established a trusted framework for validating energy flows and optimization decisions.
6. **Validation of the proposed architecture:** Experimental results confirmed the viability of the proposed architecture for a distributed energy system capable of autonomous operation, real-time environmental response, and accurate data provision for production and consumption optimization. The architecture is scalable, hardware-agnostic, and compatible with future smart grid extensions.

7.2 Original contributions

- The applicability and reliability of the OPAL-RT platform, particularly the OP5600 model, for real-time simulation of energy and control systems in both academic and industrial environments have been demonstrated.
- The implementation and design of modern energy systems, based on advanced digital technologies such as OPAL-RT platforms and real-time data acquisition and processing systems, lead to efficient, safe, and sustainable energy resource management.

- Four distinct operational scenarios for a modular electrolysis system were developed and compared under variable energy production conditions, enabling a detailed evaluation of techno-economic performance in real-world wind intermittency contexts.
- Specific optimization coefficients (CUEA, RCEH, CFO, PS, CAER, CVEH) were defined and applied to objectively and comparably quantify the performance of each scenario based on standardized indicators of efficiency, flexibility, and profitability.
- A sequential and flexible module operation strategy was validated, which simultaneously optimizes resource consumption, equipment lifespan, and production flows, reducing risks associated with frequent start-stop cycles.
- The feasibility of an autonomous energy system (Scenario 3), operating exclusively on renewable energy while maintaining high profitability and operational stability without external input, was demonstrated.
- The seasonal impact on hydrogen production was identified, along with efficient management strategies through module rotation and diversification of economic valorization channels (grid injection and tank sale).
- An integrated economic assessment model was established, quantifying monthly revenues, direct costs (energy and water), and net profit for each scenario, providing a comprehensive view of the system’s economic sustainability.
- The scientific rationale for selecting Scenario 3 as the optimal solution was supported by correlating all techno-economic performance indicators and demonstrating its advantages in terms of autonomy, efficiency, and profitability.
- A multicriteria analysis framework was developed and applied for comparative evaluation of four operational scenarios of a wind-powered green hydrogen production system, integrating relevant energy and economic indicators.
- Optimization coefficients (CUEA, CFO, CAER, PS, CVEH) were defined and used to quantify the techno-economic performance of each scenario, offering a coherent and comparable evaluation tool.
- The optimal operational scenario (Scenario 3) was determined, ensuring the best balance between operational flexibility, energy autonomy, and economic profitability, without reliance on the National Energy System (SEN).
- A detailed sensitivity analysis was conducted on the most relevant critical variables (water cost, hydrogen price in tanks, hydrogen injection price into the grid), demonstrating the economic robustness of each scenario under ±10% parameter variation.
- The correlation between wind resource seasonality and monthly economic performance was identified, highlighting the importance of an adaptive operational strategy to maximize profit and optimize electrolyzer module operation.
- The techno-economic viability of green hydrogen production under real wind intermittency conditions was validated by integrating energy simulations,

financial calculations, and comparative interpretations to support informed investment decisions.

- A modular energy monitoring platform was designed and developed, based on a distributed architecture that integrates IoT devices, software microservices, a real-time cache engine for synchronization, and a blockchain database (BigchainDB) for secure and verifiable energy data storage.
- A proprietary solution was implemented for managing asynchronous and heterogeneous data streams, using a real-time cache engine that transforms disparate sensor flows into coherent, synchronized data structures.
- A web application was developed for calculating and visualizing the renewable energy produced, enabling estimation of green energy percentage in total consumption, interactive graphical display, and result storage in a blockchain system for traceability assurance.
- Blockchain technology was integrated to secure and ensure the traceability of energy data, providing a high degree of transparency, immutability, and availability for monitoring, analysis, and energy optimization processes.
- The relationship between environmental parameters (solar radiation, temperature) and photovoltaic system performance was experimentally validated through a series of tests (Test 1, Test 2, Test 3) conducted over representative periods, with real-time analysis of current, voltage, and panel temperature.
- An original ecological performance indicator—the percentage of green energy consumed—was defined and applied to assess the system's energy autonomy and efficiency relative to photovoltaic sources and the conventional power grid.
- A synchronized graphical interface for monitoring operational parameters was developed, enabling real-time analysis of charging/discharging currents, battery voltages, delivered power, and solar radiation, offering a holistic view of the photovoltaic system's behavior.
- The practical applicability of the proposed architecture was demonstrated through successful integration of data from experimental equipment, comparative analysis over extended time intervals, and decision support for optimizing the design and operation of the energy system.

7.3 List of original publications

Report 1 – Analysis of Distributed Electricity Generation Systems and Real-Time Testing Techniques (HIL, PIL)

Report 2 – Design and Implementation of OPAL RT Modules for Testing Renewable Energy-Based Hybrid Power Systems Using Hydrogen

Report 3 – Smart Monitoring Application Using Blockchain Technology for the Lighting System in CNHPC Hall

Report 4 – Design and Testing of an Application for CO2 Emissions Reduction in a Local Community

Competitively Awarded Projects:

1. *Innovative Fuel Cell/Battery-Based Hybrid Zero Emission Power System for Maritime Transport* – Project Coordinator, Norway Grants
2. *OPTIX, Positive Energy Districts* – Project Lead, CETP

Published Books:

1. *Advancements in Renewable Energy and Green Hydrogen*, Raboaca, M.S., et al. – April 2024, 327 pages, ISBN: 9798369310144, DOI: 10.4018/979-8-3693-1014-4
2. *Clean Technologies and Sustainable Development in Civil Engineering*, Felseghi, R.-A., et al. – June 2022, 290 pages, ISBN: 9781799898108, DOI: 10.4018/978-1-7998-9810-8

Book Chapters:

1. *Hydrogen Technology Integration for Energy Support of Electric Vehicle Charging Stations*, Raboaca, M.-S., et al. – 2023, DOI: 10.4018/978-1-6684-6721-3.ch006
2. *Hybrid Energy Systems for Sustainable Buildings*, Felseghi, R.-A., et al. – 2022, DOI: 10.4018/978-1-7998-4945-2.ch005
3. *Energy Storage Systems: From Classic to Hydrogen*, Nasture, A.-M., et al. – DOI: 10.4018/978-1-7998-4945-2.ch005
4. *Synthetic Gas Production by Biomass Gasification*, Corbu, A., et al. – 2021, DOI: 10.4018/978-1-7998-4945-2.ch005
5. *OPAL-RT Technology Used in Automotive Applications for PEMFC*, Raboaca, M.S., et al. – 2021, DOI: 10.1007/978-3-030-62191-9

WOS Journals

6. [1] Pravin G. Dhawale, Vikram Kumar Kamboj, S.K. Bath, Maria Simona Raboaca, Constantin Filote, Integrating renewable energy and plug-in electric vehicles into security constrained unit commitment for hybrid power systems, Energy Reports, Volume 11, 2024, Pages 2035-2048,ISSN 23524847, https://doi.org/10.1016/j.egyr.2024.01.027.
7. [2] Gupta, A.; Saini, P.; Teja, B.S.; Durgesh, G.S.; Mishra, S.K.; Yadav, A.K.; Tanwar, S.; Alqahtani, F.; Raboaca, M.S.; Said, W. Investigating UAV-Based Applications in Indoor–Outdoor Sports Stadiums and Open-Air Gatherings for Different Interference Conditions beyond 5G Networks. *Sensors* **2023**, *23*, 6721. https://doi.org/10.3390/s23156721
8. [3] Gupta, A.; Saini, P.; Teja, B.S.; Durgesh, G.S.; Mishra, S.K.; Yadav, A.K.; Tanwar, S.; Alqahtani, F.; Raboaca, M.S.; Said, W. Investigating UAV-Based Applications in Indoor–Outdoor Sports Stadiums and Open-Air Gatherings for Different Interference Conditions beyond 5G Networks. *Sensors* **2023**, *23*, 6721. https://doi.org/10.3390/s23156721
9. [4] Jain, P.; Gupta, A.; Tanwar, S.; Alqahtani, F.; Raboaca, M.S.; Said, W. Massive MIMO NOMA: Double-Mode Model towards Green 5G Networks. *Sensors* **2023**, *23*, 6425. https://doi.org/10.3390/s23146425
10. [5] Bhattacharya, P.; Saraswat, D.; Savaliya, D.; Sanghavi, S.; Verma, A.; Sakariya, V.; Tanwar, S.; Sharma, R.; Raboaca, M.S.; Manea, D.L. Towards Future Internet: The Metaverse Perspective for Diverse IndustrialApplications. *Mathematics* **2023**, *11*, 941. https://doi.org/10.3390/math11040941
11. [6] Kumari, A.; Kakkar, R.; Gupta, R.; Agrawal, S.; Tanwar, S.; Alqahtani, F.; Tolba, A.; Raboaca, M.S.; Manea, D.L. Blockchain-Driven Real-Time Incentive Approach for Energy Management System. *Mathematics* **2023**, *11*, 928. https://doi.org/10.3390/math11040928

12. [7] Srivastava, V.; Singh, P.; Malik, P.K.; Singh, R.; Tanwar, S.; Alqahtani, F.; Tolba, A.; Marina, V.; Raboaca, M.S. Innovative Spectrum Handoff Process Using a Machine Learning-Based Metaheuristic Algorithm. *Sensors* **2023**, *23*, 2011. https://doi.org/10.3390/s23042011
13. [8] Grigoraș, G.; Raboaca, M.S.; Dumitrescu, C.; Manea, D.L.; Mihaltan, T.C.; Niculescu, V.-C.; Neagu, B.C. Contributions to Power Grid System Analysis Based on Clustering Techniques. *Sensors* **2023**, *23*, 1895. https://doi.org/10.3390/s23041895
14. [9] Rajawat, A.S.; Goyal, S.B.; Bedi, P.; Verma, C.; Ionete, E.I.; Raboaca, M.S. 5G-Enabled Cyber-Physical Systems for Smart Transportation Using Blockchain Technology. *Mathematics* **2023**, *11*, 679. https://doi.org/10.3390/math11030679
15. [10] Sindhwani, M.; Sachdeva, S.; Gupta, A.; Tanwar, S.; Alqahtani, F.; Tolba, A.; Raboaca, M.S. A Novel Context-Aware Reliable Routing Protocol and SVM Implementation in Vehicular Area Networks. *Mathematics* **2023**, *11*, 514. https://doi.org/10.3390/math11030514
16. [11] Rathod, T.; Jadav, N.K.; Tanwar, S.; Sharma, R.; Tolba, A.; Raboaca, M.S.; Marina, V.; Said, W. Blockchain-Driven Intelligent Scheme for IoT-Based Public Safety System beyond 5G Networks. Sensors 2023, 23, 969. https://doi.org/10.3390/s23020969
17. [12] Shah, H.; Shah, D.; Jadav, N.K.; Gupta, R.; Tanwar, S.; Alfarraj, O.; Tolba, A.; Raboaca, M.S.; Marina, V. Deep Learning-Based Malicious Smart Contract and Intrusion Detection System for IoT Environment. *Mathematics* **2023**, *11*, 418. https://doi.org/10.3390/math11020418
18. [13] Enescu, F.M.; Birleanu, F.G.; Raboaca, M.S.; Raceanu, M.; Bizon, N.; Thounthong, P. Electric Vehicle Charging Station Based on Photovoltaic Energy with or without the Support of a Fuel Cell–Electrolyzer Unit. *Energies* **2023**, *16*, 762. https://doi.org/10.3390/en16020762
19. [14] Jain, A.; Verma, C.; Kumar, N.; Raboaca, M.S.; Baliya, J.N.; Suciu, G. Image Geo-Site Estimation Using Convolutional Auto-Encoder and Multi-Label Support Vector Machine. *Information* **2023**, *14*, 29. https://doi.org/10.3390/info14010029
20. [15] Molla, J.P.; Dhabliya, D.; Jondhale, S.R.; Arumugam, S.S.; Rajawat, A.S.; Goyal, S.B.; Raboaca, M.S.; Mihaltan, T.C.; Verma, C.; Suciu, G. Energy Efficient Received Signal Strength-Based Target Localization and Tracking Using Support Vector Regression. *Energies* **2023**, *16*, 555. https://doi.org/10.3390/en16010555
21. [16] Sheikh, Z.A.; Singh, Y.; Tanwar, S.; Sharma, R.; Turcanu, F.-E.; Raboaca, M.S. EISM-CPS: An Enhanced Intelligent Security Methodology for Cyber-Physical Systems through Hyper-Parameter Optimization. *Mathematics* **2023**, *11*, 189. https://doi.org/10.3390/math11010189
22. [17] Bhatia, J.; Italiya, K.; Jadeja, K.; Kumhar, M.; Chauhan, U.; Tanwar, S.; Bhavsar, M.; Sharma, R.; Manea, D.L.; Verdes, M.; et al. An Overview of Fog Data Analytics for IoT Applications. *Sensors* **2023**, *23*, 199. https://doi.org/10.3390/s23010199
23. [18] Nagaraj, S.; Kathole, A.B.; Arya, L.; Tyagi, N.; Goyal, S.B.; Rajawat, A.S.; Raboaca, M.S.; Mihaltan, T.C.; Verma, C.; Suciu, G. Improved Secure Encryption with Energy Optimization Using Random Permutation Pseudo Algorithm Based on Internet of Thing in Wireless Sensor Networks. *Energies* **2023**, *16*, 8. https://doi.org/10.3390/en16010008
24. [19] Kakkar, R.; Gupta, R.; Agrawal, S.; Tanwar, S.; Sharma, R.; Alkhayyat, A.; Neagu, B.-C.; Raboaca, M.S. A Review on Standardizing Electric Vehicles

Community Charging Service Operator Infrastructure. *Appl. Sci.* **2022**, *12*, 12096. https://doi.org/10.3390/app122312096
25. [20] Dhabliya, D.; Soundararajan, R.; Selvarasu, P.; Balasubramaniam, M.S.; Rajawat, A.S.; Goyal, S.B.; Raboaca, M.S.; Mihaltan, T.C.; Verma, C.; Suciu, G. Energy-Efficient Network Protocols and Resilient Data Transmission Schemes for Wireless Sensor Networks—An Experimental Survey. *Energies* **2022**, *15*, 8883. https://doi.org/10.3390/en15238883
26. [21] Filote C, Felseghi R-A, Raboaca MS, Aşchilean I. Environmental impact assessment of green energy systems for power supply of electric vehicle charging station. *Int J Energy Res*. 2020; 44: 10471–10494. **https://doi.org/10.1002/er.5678**
27. [22] Bizon, N.; Oproescu, M.; Thounthong, P.; Varlam, M.; Carcadea, E.; Culcer, M.; Iliescu, M.; Raboaca, M.S.; Sorlei, I.S. Improving the Fuel Economy and Battery Lifespan in Fuel Cell/Renewable Hybrid Power Systems Using the Power-Following Control of the Fueling Regulators. *Appl. Sci.* **2020**, *10*, 8310. https://doi.org/10.3390/app10228310
28. [23] Raboaca, M.S.; Bizon, N.; Trufin, C.; Enescu, F.M. Efficient and Secure Strategy for Energy Systems of Interconnected Farmers′ Associations to Meet Variable Energy Demand. *Mathematics* **2020**, *8*, 2182. https://doi.org/10.3390/math8122182
29. [24] Meheden, M.; Musat, A.; Traciu, A.; Viziteu, A.; Onu, A.; Filote, C.; Răboacă, M.S. Design Patterns and Electric Vehicle Charging Software. *Appl. Sci.* **2021**, *11*, 140. https://doi.org/10.3390/app11010140
30. [25] Felseghi, R.-A.; Aşchilean, I.; Cobîrzan, N.; Bolboacă, A.M.; Raboaca, M.S. Optimal Synergy between Photovoltaic Panels and Hydrogen Fuel Cells for Green Power Supply of a Green Building—A Case Study. *Sustainability* **2021**, *13*, 6304. https://doi.org/10.3390/su13116304
31. [26] Felseghi, R.-A.; Aşchilean, I.; Cobîrzan, N.; Bolboacă, A.M.; Raboaca, M.S. Optimal Synergy between Photovoltaic Panels and Hydrogen Fuel Cells for Green Power Supply of a Green Building—A Case Study. *Sustainability* **2021**, *13*, 6304. https://doi.org/10.3390/su13116304
32. [27] Raboaca MS, Bizon N, Grosu OV. Optimal energy management strategies for the electric vehicles compiling bibliometric maps. *Int J Energy Res*. 2021; 45: 10129–10172. **https://doi.org/10.1002/er.6503**
33. [28] Dhawankar, P.; Agrawal, P.; Abderezzak, B.; Kaiwartya, O.; Busawon, K.; Raboacă, M.S. Design and Numerical Implementation of V2X Control Architecture for Autonomous Driving Vehicles. *Mathematics* **2021**, *9*, 1696. https://doi.org/10.3390/math9141696
34. [29] Răboacă MS, Bizon N, Thounthong P. Intelligent charging station in 5G environments: Challenges and perspectives. *Int J Energy Res*. 2021; 45(11): 16418–16435. **https://doi.org/10.1002/er.6889**
35. [30] Kumari, A.; Chintukumar Sukharamwala, U.; Tanwar, S.; Raboaca, M.S.; Alqahtani, F.; Tolba, A.; Sharma, R.; Aschilean, I.; Mihaltan, T.C. Blockchain-Based Peer-to-Peer Transactive Energy Management Scheme for Smart Grid System. *Sensors* **2022**, *22*, 4826. https://doi.org/10.3390/s22134826
36. [31] Raboaca MS, Meheden M, Musat A, et al. An overview and performance evaluation of open charge point protocol from an electromobility concept perspective. *Int J Energy Res*. 2022; 46(2): 523-543. doi:**10.1002/er.7206**

37. [32] Flocea, R.; Hîncu, A.; Robu, A.; Senocico, S.; Traciu, A.; Remus, B.M.; Răboacă, M.S.; Filote, C. Electric Vehicle Smart Charging Reservation Algorithm. *Sensors* **2022**, *22*, 2834. https://doi.org/10.3390/s22082834
38. [33] Viziteu, A.; Furtună, D.; Robu, A.; Senocico, S.; Cioată, P.; Remus Baltariu, M.; Filote, C.; Răboacă, M.S. Smart Scheduling of Electric Vehicles Based on Reinforcement Learning. *Sensors* **2022**, *22*, 3718. https://doi.org/10.3390/s22103718
39. [34] Tanwar, S.; Kumari, A.; Vekaria, D.; Raboaca, M.S.; Alqahtani, F.; Tolba, A.; Neagu, B.-C.; Sharma, R. *GrAb*: A Deep Learning-Based Data-Driven Analytics Scheme for Energy Theft Detection. *Sensors* **2022**, *22*, 4048. https://doi.org/10.3390/s22114048
40. [35] Rathod, T.; Jadav, N.K.; Alshehri, M.D.; Tanwar, S.; Sharma, R.; Felseghi, R.-A.; Raboaca, M.S. Blockchain for Future Wireless Networks: A Decade Survey. *Sensors* **2022**, *22*, 4182. https://doi.org/10.3390/s22114182
41. [36] Mankodiya, H.; Jadav, D.; Gupta, R.; Tanwar, S.; Alharbi, A.; Tolba, A.; Neagu, B.-C.; Raboaca, M.S. XAI-Fall: Explainable AI for Fall Detection on Wearable Devices Using Sequence Models and XAI Techniques. *Mathematics* **2022**, *10*, 1990. https://doi.org/10.3390/math10121990
42. [37] Kaur, M.; Gupta, S.; Kumar, D.; Verma, C.; Neagu, B.-C.; Raboaca, M.S. Delegated Proof of Accessibility (DPoAC): A Novel Consensus Protocol for Blockchain Systems. *Mathematics* **2022**, *10*, 2336. https://doi.org/10.3390/math10132336
43. [38] Sandesara, M.; Bodkhe, U.; Tanwar, S.; Alshehri, M.D.; Sharma, R.; Neagu, B.-C.; Grigoras, G.; Raboaca, M.S. Design and Experience of Mobile Applications: A Pilot Survey. *Mathematics* **2022**, *10*, 2380. https://doi.org/10.3390/math10142380
44. [39] Kakkar, R.; Gupta, R.; Agrawal, S.; Bhattacharya, P.; Tanwar, S.; Raboaca, M.S.; Alqahtani, F.; Tolba, A. Blockchain and Double Auction-Based Trustful EVs Energy Trading Scheme for Optimum Pricing. Mathematics 2022, 10, 2748. https://doi.org/10.3390/math10152748
45. [40] Kumari, A.; Patel, R.K.; Sukharamwala, U.C.; Tanwar, S.; Raboaca, M.S.; Saad, A.; Tolba, A. AI-Empowered Attack Detection and Prevention Scheme for Smart Grid System. *Mathematics* **2022**, *10*, 2852. https://doi.org/10.3390/math10162852
46. [41] Tanwar S, Kakkar R, Gupta R, et al. Blockchain-based electric vehicle charging reservation scheme for optimum pricing. *Int J Energy Res*. 2022; 46(11): 14994-15007. doi:10.1002/er.8199
47. [42] Trivedi, M.; Kakkar, R.; Gupta, R.; Agrawal, S.; Tanwar, S.; Niculescu, V.-C.; Raboaca, M.S.; Alqahtani, F.; Saad, A.; Tolba, A. Blockchain and Deep Learning-Based Fault Detection Framework for Electric Vehicles. *Mathematics* **2022**, *10*, 3626. https://doi.org/10.3390/math10193626
48. [43] Kakkar, R.; Gupta, R.; Agrawal, S.; Tanwar, S.; Altameem, A.; Altameem, T.; Sharma, R.; Turcanu, F.-E.; Raboaca, M.S. Blockchain and IoT-Driven Optimized Consensus Mechanism for Electric Vehicle Scheduling at Charging Stations. *Sustainability* **2022**, *14*, 12800. https://doi.org/10.3390/su141912800
49. [44] Enescu, F.M.; Birleanu, F.G.; Raboaca, M.S.; Bizon, N.; Thounthong, P. A Review of the Public Transport Services Based on the Blockchain Technology. *Sustainability* **2022**, *14*, 13027. https://doi.org/10.3390/su142013027
50. [45] Abhay Bhatia, Anil Kumar, Arpit Jain, Adesh Kumar, Chaman Verma, Zoltan Illes, Ioan Aschilean, Maria Simona Raboaca, Networked control system with MANET

communication and AODV routing, Heliyon, Volume 8, Issue 11, 2022, e11678, ISSN 2405-8440, DOI: 10.1016/j.heliyon.2022.e11678

51. [46] Singh, S.; Singh, J.; Singh, S.; Goyal, S.B.; Raboaca, M.S.; Verma, C.; Suciu, G. Detection and Mitigation of GNSS Spoofing Attacks in Maritime Environments Using a Genetic Algorithm. *Mathematics* **2022**, *10*, 4097, https://doi.org/10.3390/math10214097

Papers in Databases Recognized by CNATDCU

52. [1] A Novel Hybrid Machine Learning Framework for Wind Speed Prediction, Mohamed Yassine Rhafes, Omar Moussaoui, Maria Simona Raboaca and Traian Candin Mihaltan, E3S Web Conf., 601 (2025) 00067, DOI: https://doi.org/10.1051/e3sconf/202560100067
53. [2] Rhafes, M.Y., Moussaoui, O., Raboaca, M.S. (2025). Feature Selection Techniques for Linear Regression in Solar Irradiance Forecasting. In: Farhaoui, Y., Herawan, T., Imoize, A.L., Allaoui, A.E. (eds) Intersection of Artificial Intelligence, Data Science, and Cutting-Edge Technologies: From Concepts to Applications in Smart Environment. ICAISE 2024. Lecture Notes in Networks and Systems, vol 1353. Springer, Cham. https://doi.org/10.1007/978-3-031-88304-0_18
54. [3] Chiliment, Alexandra-Valentina & Tiron, Florina-Gabriela & Voicu, Andreea-Gabriela & Enescu, Florentina & Dragusin, Sebastian & Bizon, Nicu & Răboacă, Maria-Simona. (2024). A Study of Intelligent Parking: Urban Efficiency Through Advanced Automated Systems Based on Green Energy Management. 1-7. 10.1109/ECAI61503.2024.10607568, https://dblp.dagstuhl.de/pid/383/0780.html
55. [4] Rhafes, M.Y.; Moussaoui, O.; Raboaca, M.S.; Betari, A. Analysis and Prediction of Green Hydrogen Production Potential Using Deep Learning in Tan-Tan, 20 March 2025, Published by Springer Nature, p. 541-551, https://doi.org/10.1007/978-981-96-0644-3_49
56. [5] Pant, Piyush & Rajawat, Anand & Goyal, S B & Kemat, Baharu & Mihălţan, Traian & Verma, Chaman & Răboacă, Maria. (2023). Machine Learning Techniques for Analysis of Mars Weather Data. 1-7. 10.1109/ECAI58194.2023.10194233, DOI:10.1109/ECAI58194.2023.10194233
57. [6] Dhawale, Pravin & Kumar, Vikram & Bath, S.K. & Verma, Chaman & Raboaca, Maria & Filote, Constantin & Kumar, Deepak. (2023). Optimal Sizing of Security Constrained Unit Commitment Problem Integrated with Renewable Energy Sources and PEVs. 01-05. 10.1109/ECAI58194.2023.10194085, DOI:10.1109/ECAI58194.2023.10194085
58. [7] G. Anusha et al., "Performance Comparison of 15-Level Multilevel Inverter Topologies," 2023 15th International Conference on Electronics, Computers and Artificial Intelligence (ECAI), Bucharest, Romania, 2023, pp. 01-06, doi: 10.1109/ECAI58194.2023.10194137.
59. [8] Culcer, Mihai & Iliescu, Mariana & Raboaca, Maria & Raceanu, Mircea & Enache, Adrian & Carcadea, Elena. (2023). P2G2P System - Case Study for A 5 MW Photovoltaic Park. 01-08. 10.1109/ECAI58194.2023.10194064, DOI:10.1109/ecai58194.2023.10194064
60. [9] Rata, Mihai & Rata, Gabriela & Constantin, Filote & Ciprian, Afanasov & Simona, Raboaca. (2020). Design of EV Charging Station Controlled by PLC. 189-192. 10.1109/EPE50722.2020.9305523, **https://doi.org/10.3390/en13010176**
61. [10] Felseghi, Raluca & Raboaca, Maria & Bolboaca, Andrei. (2020). SIMULATION MODEL FOR DESIGNING A HYBRID ENERGY SYSTEM FOR RESIDENTIAL APPLICATION. 435-442. 10.5593/sgem2020/6.1/s26.057, DOI:10.5593/sgem2020/6.1/s26.057

62. [11] N. Bizon, E. Carcadea, M. Iliescu, M. S. Raboaca, I. Manta and S. I. Sorlei, "Estimation of hydrogen consumption for proton-exchange membrane fuel cells systems," *2021 13th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*, Pitesti, Romania, 2021, pp. 1-7, doi: 10.1109/ECAI52376.2021.9515021.
    [12] Raboaca, Maria & Bizon, Nicu & Oana - Vasilica, Grosu & Carcadea, Elena & Filote, Constantin & Milici, Laurentiu. (2021). Fuell cell/ Photovoltaic panels/ Wind turbines Hybrid Systems analysed through bibliometric maps. 1-7. 10.1109/ECAI52376.2021.9515062.
63. [13] Bizon, Nicu & Oproescu, M. & Carcadea, Elena & Raceanu, Mircea & Raboaca, Maria & Sorlei, Ioan-Sorin. (2021). Performance of the Fuel Economy Strategies for Fuel Cell Systems under Power Tracking Control. 1-5. 10.1109/ECAI52376.2021.9515176, DOI:10.1016/j.apenergy.2019.113400
64. [14] Bizon, Nicu & Takorabet, Noureddine & Thounthong, Phatiphat & Carcadea, Elena & Raboaca, Maria & Sorlei, Ioan-Sorin. (2022). Power-following strategy for microgrids based on multiple renewable/fuel cells systems. 1-6. 10.1109/ECAI54874.2022.9847467, DOI:10.1109/ECAI54874.2022.9847467
65. [15] P. Pant *et al*., "Blockchain for AI-Enabled Industrial IoT with 5G Network," *2022 14th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*, Ploiesti, Romania, 2022, pp. 1-4, doi: 10.1109/ECAI54874.2022.9847428, DOI:10.1007/978-981-99-6544-1_16
66. [16] Enescu, Florentina & Raboaca, Maria & Bizon, Nicu & Ionescu, Valeriu. (2022). Assessment of Home Charging Station feeding electric vehicle using PV - Green Energy. 1-6. 10.1109/ECAI54874.2022.9847463, DOI:10.1109/ECAI54874.2022.9847463
67. [17] Rajawat, Anand & Goyal, S B & Bedi, Pradeep & Mihaltan, Traian & Neagu, Bogdan & Raboaca, Maria & Verma, Chaman. (2022). Electrical Fault Detection for Industry 4.0 using Fusion deep Learning Algorithm. 658-662. 10.1109/EPE56121.2022.9959762, DOI:10.1109/EPE56121.2022.9959762
68. [18] Ravi, Renjith & Raboaca, Maria & Goyal, S B & Verma, Chaman & Neagu, Bogdan. (2022). A Low-Cost Industrial Automation System Using IoT and Cloud Computing. 10.1109/EPE56121.2022.9959772, **DOI:** 10.1109/EPE56121.2022.9959772
69. [19] Loganathan, N & Prasanth, J & Saravanan, R & Jayasuriya, Vimukthi & Karthikeyan, S. (2021). Smart Substation Monitoring and Control. 657-661. 10.1109/ICACCS51430.2021.9442002, DOI:10.1109/ICACCS51430.2021.9442002
70. [21] Pant, Piyush & Rajawat, Anand & Goyal, S B & Singh, Deepmala & Neagu, Bogdan & Raboaca, Maria & Verma, Chaman. (2022). Using Machine Learning for Industry 5.0 Efficiency Prediction Based on Security and Proposing Models to Enhance Efficiency. 909-914. 10.1109/SMART55829.2022.10047387, DOI:10.1109/SMART55829.2022.10047387
71. [22] Rajawat, Anand & Goyal, S B & Bedi, Pradeep & Neagu, Bogdan & Raboaca, Maria & Verma, Chaman. (2022). Cyber-Physical System for Industrial Automation Using Quantum Deep Learning. 897-903. 10.1109/SMART55829.2022.10047730, DOI:10.1109/SMART55829.2022.10047730
72. [23] V. K. Kamboj, A. B. Krishna, C. Verma, M. S. Raboaca, C. Filote and M. Stepanova, "Chaotic American zebra search optimization algorithm for benchmark challenges," *2023 15th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*, Bucharest, Romania, 2023, pp. 1-5, doi: 10.1109/ECAI58194.2023.10194001.
73. [24] Rajawat, Anand & Goyal, S B & Goyal, Aarti & Rajawat, Kavita & Raboaca, Maria & Verma, Chaman & Mihaltan, Traian. (2023). Enhancing Security and Scalability of Metaverse with Blockchain-based Consensus Mechanisms. 01-06.

10.1109/ECAI58194.2023.10194035, DOI:10.1109/ECAI58194.2023.10194035
74. [25] Rajawat, Anand & Goyal, S B & Solanki, RamKumar & Raboaca, Maria & Mihaltan, Traian & Illés, Zoltán & Verma, Chaman. (2023). Blockchain-based Security Framework for Metaverse: A Decentralized Approach. 01-06. 10.1109/ECAI58194.2023.10193962, DOI:10.1109/ECAI58194.2023.10193962
75. [26] Narayan, Saraswati & Kumar, Dr. Neerendra & Koul, Neha & Verma, Chaman & Enescu, Florentina & Raboaca, Maria. (2023). Hybrid Approach for Resource Allocation and Task Scheduling on Cloud Computing: A Review. 10.1007/978-981-19-9876-8_40, DOI:10.1007/978-981-19-9876-8_40
76. [27] Kaur, M., Gupta, S., Kumar, D., Raboaca, M.S., Goyal, S.B., Verma, C. (2023). IPFS: An Off-Chain Storage Solution for Blockchain. In: Singh, Y., Singh, P.K., Kolekar, M.H., Kar, A.K., Gonçalves, P.J.S. (eds) Proceedings of International Conference on Recent Innovations in Computing. Lecture Notes in Electrical Engineering, vol 1001. Springer, Singapore. https://doi.org/10.1007/978-981-19-9876-8_39
77. [28] Haq, Inam & Hassan, Inzimam & Shah, Hilal. (2023). Machine Learning Techniques for Result Prediction of One Day International (ODI)Cricket Match. 1-5. 10.1109/I2CT57861.2023.10126241, **DOI:** 10.1109/I2CT57861.2023.10126241
78. [29] Chouhan, Robin & Rajawat, Anand & Goyal, S B & Bedi, Pradeep & Neagu, Bogdan & Raboaca, Maria & Verma, Chaman. (2022). Experimental Analysis for Position Estimation using Trilateration and RSSI in Industry 4.0. 904-908. 10.1109/SMART55829.2022.10047276, DOI: 10.1007/978-981-19-1742-4_38
79. [30] Raboaca, Maria-Simona & Mihaltan, Traian. (2023). Hydrogen Technology Integration for Energy Support of Electric Vehicle Charging Stations. 10.4018/978-1-6684-6721-3.ch006, **DOI:** 10.4018/978-1-6684-6721-3.ch006

7.4 Perspectives for further developments

- **Extension of the platform toward a multi-source system** by integrating additional forms of renewable energy (wind, geothermal, hydroelectric) in order to evaluate the synergistic behavior of a hybrid energy system operating under partial or full autonomy.
- **Implementation of artificial intelligence (AI) and machine learning algorithms** aimed at forecasting photovoltaic production, detecting operational anomalies, and automatically optimizing energy storage and consumption strategies.
- **Scaling the software architecture to the level of an urban or rural microgrid**, with the possibility of integration into smart grids and active participation of prosumers (producer-consumers) in the energy market.
- **Automation of energy source switching decisions**, based on cost, demand, solar radiation levels, or the status of the storage system, using an advanced energy management system (EMS) based on fuzzy logic, multi-objective optimization, or adaptive control.
- **Expansion of the web application's functionalities** by implementing customizable dashboards, automatic alerts, and notifications regarding the exceeding of certain operational thresholds, as well as developing a mobile interface for remote monitoring.

- **Integration of a peer-to-peer (P2P) energy trading platform**, based on smart contracts and blockchain, enabling locally generated renewable energy to be securely and decentrally traded among participants.

Bibliography

[1] https://energie.gov.ro/strategia-energetica-nationala/, accesat in 06.06.2025

[2]https://commission.europa.eu/strategy-and-policy/eu-budget/eu-borrower-investor-relations/nextgenerationeu_en, accesat in 06.06.2025

[3] https://commission.europa.eu/business-economy-euro/economic-recovery/recovery-and-resilience-facility_ro, accesat in 06.06.2025

[4] https://proiecte.pnrr.gov.ro/#/home, accesat in 06.06.2025

[5]https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_ro, accesat in 06.06.2025

[6] https://ourworldindata.org/grapher/modern-renewable-prod?country=~OWID_EUR, accesat in 06.06.2025

[7] M. Thema, F. Bauer, M. Sterner - Power-to-Gas: Electrolysis and methanation status review, Renewable and Sustainable Energy Reviews, Vol. 112, 2019, pp. 775-787

[8] https://www.mathworks.com/products/simulink.html, accesat in 06.06.2025

[9] https://www.trnsys.com/, accesat in 06.06.2025

[10] https://ihoga.unizar.es/en/, accesat in 06.06.2025

[11] https://openmodelica.org/, accesat in 06.06.2025

[12] https://www.opal-rt.com/, accesat in 06.06.2025

[13] https://www.opal-rt.com/systems-efpgasim/, accesat in 06.06.2025

[14] https://www.opal-rt.com/systems-ephasorsim/, accesat in 06.06.2025

[15] https://www.opal-rt.com/system-emegasim/, accesat in 06.06.2025

[16] https://www.opal-rt.com/systems-hypersim/, accesat in 06.06.2025

[17] www.lazard.com: "Levelized Cost of Energy and Levelized Cost of Storage, 2018", accesata in 24.06.2024
https://www.lazard.com/research-insights/levelized-cost-of-energy-and-levelized-cost-of-storage-2018/

[18] Juan Montoya, Ron Brandl, Keerthi Vishwanath et. al., Advanced Laboratory Testing Methods Using Real-Time Simulation and Hardware-in-the-Loop Techniques: A Survey of Smart Grid International Research Facility Network Activities, Energies 2020, 13, 3267, DOI:10.3390/en13123267

[19] Bermudez, O. Gomozov, X. Kestelyn, F. Barrero, N.K. Nguyen, E. Semail, Model predictive optimal control considering current and voltage limitations: Real-time validation using OPAL-RT technologies and five-phase permanent magnet synchronous machines, Mathematics and Computers in Simulation, Volume 158, 2019, Pages 148-161, 10.1016/j.matcom.2018.07.005.
DOI:10.1016/j.matcom.2018.07.005

[20] Bian, Desong & Kuzlu, Murat & Pipattanasomporn, Manisa & Rahman, Saifur & Wu, Yiming. (2015). Real-time co-simulation platform using OPAL-RT and OPNET for analyzing smart grid performance. 1-5. 10.1109/PESGM.2015.7286238.
DOI:10.1109/PESGM.2015.7286238