UNIVERSITY POLITEHNICA OF BUCHAREST

Faculty of Power Engineering

Doctoral School of Energy Engineering

SUMMARY

PhD THESIS

INTEGRATION AND OPTIMAL OPERATION OF STORAGE INSTALLATIONS IN THE NATIONAL ENERGY SYSTEM IN THE PRESENCE OF RENEWABLE SOURCES

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Keywords: storage installations, prosumers, renewable sources, energy transition, non-renewable sources.

INTRODUCTION

Electricity has fundamentally transformed human progress in an irreversible manner, effectively permeating every aspect of social life. Modern society could no longer exist without electricity in the form it is used today.

Currently, the increase in electricity consumption is tempered by the impact of technological development, but in the future, electricity is expected to be integrated into an ever-growing number of technical applications, intensifying humanity's dependence on this energy resource.

Renewable energy sources have become a major development focus worldwide due to the European Union's directive to reduce greenhouse gas emissions and address the growing electricity demand through the introduction of electric transport means.

Intense concern for limiting environmental pollution, the current political and economic context, as well as ensuring the adequacy of the national electrical system, has led to the increased development and exploitation of renewable energy sources and the enhancement of electrical energy storage capacities.

The European Union's directive on renewable energy has stimulated heightened interest in member states for the development of renewable energy sources, with a special focus on wind and solar energy.

Energy production from wind and solar power plants is intermittent throughout the year and cannot be regulated in the same manner as traditional power plants. To ensure adequate energy supply, it is essential to have available production capacity in conventional power plants that can be quickly activated or in energy storage capacities.

The national electrical system has recently undergone changes in its production source structure, rapidly adapting to facilitate the inclusion of a wider range of renewable energy sources, including energy storage installations.

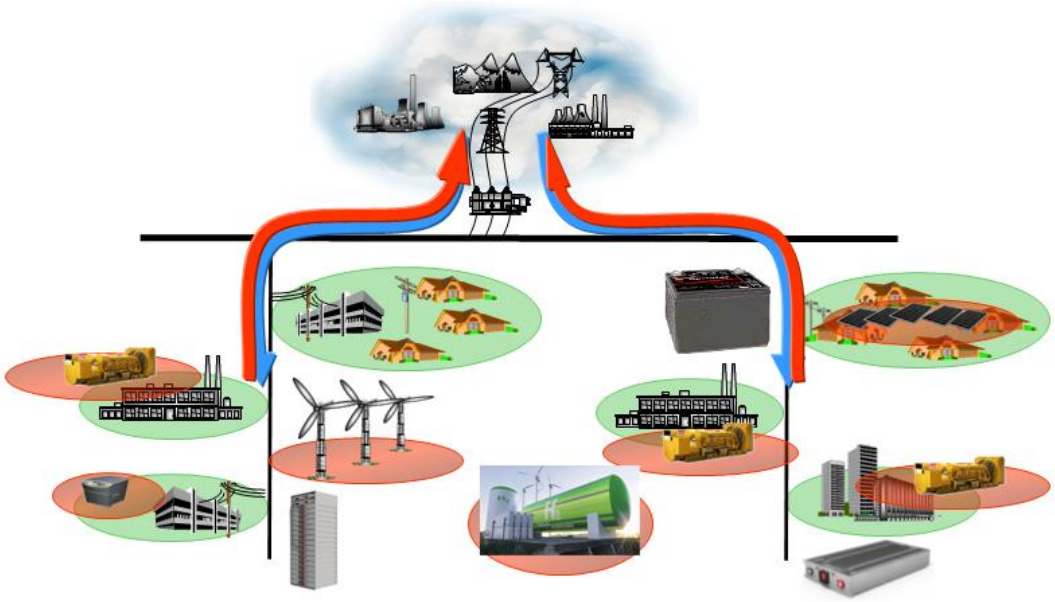


Fig. 1 Composition of the National Energy System (SEN) and Integration of Storage Installations

Although the future belongs to renewable resources, the ability to store electrical energy will be a major challenge for maintaining a balanced and efficient electrical system.

Energy storage installations (IS) will contribute to stabilizing the electricity balancing market by smoothing out consumption peaks in the day-ahead market (PZU), which is still in its early stages of organization and operation.

Optimized balancing markets will ensure supply security at minimal costs and can offer environmental benefits by reducing the need for active power reserves.

The integration and optimal operation of storage installations in the National Energy System (SEN) aims to:

-Cover the technological self-consumption of network operators

-Ensure the adequacy of the SEN

-Assist the electricity balancing market by smoothing out peaks in the day-ahead market (PZU)

-Store electrical energy in areas with a high concentration of renewable resources such as wind and solar

-Stabilize the electrical grid by providing frequency regulation services for the SEN

-Play a key role between the production and consumption of electrical energy

-Contribute to a more sustainable planet through a harmonized energy system that is ready to include a greater variety of renewable sources, thus increasing system flexibility

-Optimize the use of electrical energy

-Conserve the environment and reduce greenhouse gas emissions (GHG)

-Foster research, development, and competitiveness in the field of energy storage and its utilization when needed by the system

-Enhance consumer flexibility

-Reduce imbalances in power system control (CPT)

-Shorten the payback period for investments in the National Energy System

-Improve energy autonomy for users at various levels within electrical networks

A complete transition to energy derived exclusively from renewable energy sources (RES) and storage installations (SI) involves substantial economic costs, which will be reflected in consumer bills. Therefore, it is crucial to be aware of and understand the entire energy chain from production to consumption, based on an appropriate set of regulatory norms to encourage the use of renewable energy sources and storage installations.

This doctoral thesis is organized into four key chapters, preceded by an introduction and followed by a concluding chapter that includes conclusions, contributions, fundamental concepts, and essential provisions. It also includes lists of figures, tables, and abbreviations used in the text, as well as a bibliography. Additionally, a list of the author's publications during the doctoral studies is provided at the end of the document.

The initial chapter focuses on theoretical aspects of renewable energy sources and storage installations within the National Energy System (SEN), examining their structure, operation, development, and the challenges associated with their integration into the grid.

In this chapter, the current status of SEN and the potential for covering system services are presented, discussing a system in continuous motion and a new approach to types of electric energy sources, along with an analysis of the evolution of production, consumption, and balance within SEN. The chapter also presents and analyzes the evolution of the average electricity price on the day-ahead market (PZU) and evaluates greenhouse gas emissions (GHG).

The chapter concludes with an overview of the targets set by the EU through the National Recovery and Resilience Plan (PNRR) and the National Integrated Energy and Climate Plan (PNIESC) regarding renewable energy sources and storage installations.

Chapter two presents a holistic view of renewable sources, storage installations, and the potential replacement of non-renewable sources such as coal, oil, and gas. This chapter also analyzes the integration and optimization of various technologies for carbon emission reduction in other countries and methods for replacing non-renewable energy sources. It is noted that the Polish experience can be very useful for Romania. Poland provides a framework for the growth of energy communities, encouraging the development of energy clusters with new regulations and business models where value sharing is crucial for the growth and stability of energy communities.

Similar steps should be followed in Romania to form coalitions of consumers and encourage communities to develop, making their members less affected by energy poverty and geopolitical instability.

Chapter three (case study) presents in detail the possibilities for connecting two storage installations to the electrical grid: the Tarnița Pumped-Storage Hydroelectric Plant (CHEAP Tarnița 1000 MW) and the Freeflow Battery Storage Installation (IS Freeflow 1000 MW), considering the specific characteristics of these types of plants. The

chapter examines both the impact of their connection on the National Transmission Grid and potential limitations the grid may impose on these storage installations.

The chapter concludes with a synthesis of the results obtained from the case study, which assessed the effectiveness of integrating a storage installation into the transmission grid and its impact on the balancing market.

Chapter four aims to analyze the electricity production/consumption and the storage requirements for two typical photovoltaic installation examples with different user types:

-An active consumer in the Bucharest area (prosumer, grid-connected).

-A residential consumer in the Călărași area (consumer, off-grid connection), who has a photovoltaic installation and a battery storage system.

The research is based on existing data obtained from personal households, inverter data, prices from various manufacturers and suppliers, accumulated technical knowledge, and experience in the national electricity sector, a sector in continuous motion and development.

The operational characteristics of photovoltaic panels and storage installations for the two users were analyzed over the specified periods, and reasonable hypotheses were made considering the type of grid connection and off-grid setup.

The results provided valuable insights for decision-makers regarding the potential to become an active consumer (prosumer). They demonstrated the feasibility of storage installations and the importance of optimizing consumption through various technologies, such as smart plugs with Wi-Fi and smartphone applications. These smart devices enable active consumers to optimize their consumption, smoothing out evening peaks.

By shifting the usage away from evening peaks, active consumers can utilize the entire amount of generated renewable energy and achieve a much lower total energy cost, as the amount of energy purchased from the supplier will be significantly reduced. It is evident that there is a correlation between the energy purchased from the supplier and the active consumer’s load curve.

The final part of the project is dedicated to final conclusions, personal contributions, and future development perspectives.

This scientific research contributes to the integration and optimal operation of storage installations in the national energy system, with implications for the balancing market, based on concrete information from the Romanian electricity system. It highlights my commitment to conducting studies with direct applicability in the country.

This doctoral thesis represents a continuation of my research efforts and will lead to obtaining exceptionally useful results for the electricity system. The theoretical aspects resolved and the practical applications that can be developed provide the proposed study with significant scientific value and potential for expanding current knowledge.

1. PRESENTATION OF RENEWABLE SOURCES AND STORAGE INSTALLATIONS IN THE NATIONAL ENERGY SYSTEM

1.1 Onshore/Offshore Wind Power Plants

Types of Wind Power Plants

Currently, various technologies are available on the market for generating electrical energy from wind, classified by the type of generator used and its method of grid integration. Main examples include constant-speed wind turbines, which operate with squirrel-cage asynchronous generators and are directly connected to the grid, and variable-speed turbines. Variable-speed turbines are further divided based on the type of generator used: asynchronous or synchronous. The wound-rotor asynchronous generator is used either in a doubly-fed arrangement, incorporating a bidirectional converter in the rotor circuit, or with Optislip technology, which involves variable resistance on the rotor. On the other hand, the synchronous generator can be equipped with permanent magnets or have standard excitation. In both cases, connecting the generator to the grid is done through a bidirectional converter, which is usually larger than the one used for the wound-rotor asynchronous generator.

The energy produced by wind installations

The primary energy that drives the blades of a wind turbine comes from the movement of air masses, caused by temperature variations on the Earth's surface.

The kinetic energy W captured from the air mass m with a velocity v_1 before the blades and v_2 after the blades of a wind turbine (see Fig. 2) can be calculated using the formula:

$$W = \frac{1}{2} \cdot m \cdot (v_1^2 - v_2^2)$$

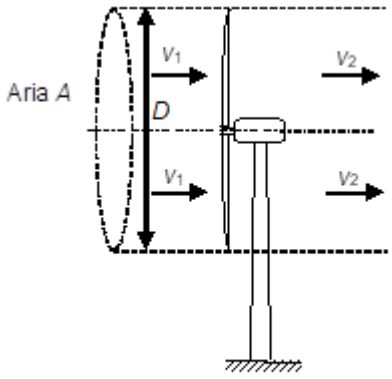


Fig. 2 wind turbine

1.2 Photovoltaic Power Plants

The photovoltaic effect occurs when light strikes a semiconductor material, increasing the mobility of its electrons. The voltage then drives the electrons in a directed manner, thereby generating electric current. Electric current is the flow of controlled electrical charges.

Photovoltaic energy is the energy produced by photovoltaic cells, which convert sunlight directly into direct current (DC) electricity. Multiple photovoltaic cells make up a photovoltaic panel, and several photovoltaic panels together form a photovoltaic power plant, as shown in Fig. 3.



Fig. 3 Photovoltaic Cell and Panel

Photovoltaic cells are made from silicon, an element from the group of crystal-formers. It is the third most abundant element on Earth, after oxygen and hydrogen, and is found in nature in the form of compounds such as silica (sand, quartz, cristobalite) or silicates (feldspar, kaolin). Silicon is not considered toxic and, through technological processes, metallurgical silicon with a purity of 98% is extracted.

Types of Photovoltaic Cells:

-Monocrystalline Cells
-Polycrystalline Cells
-Amorphous Cells
-Tandem Cells
-Thin-Film Cells
-Polymer Cells

Energy Produced by Photovoltaic Installations

The amount of solar radiation reaching the Earth's surface is variable. Depending on the apparent movement of the Sun, this amount of solar radiation fluctuates, influenced also by the composition of the atmosphere and the presence of clouds in the sky.
The formula describing the relationship between current and voltage for a photovoltaic cell is:

$$I = I_d - I_L = I_0\left(e^{\frac{eU}{kT}} - 1\right) - I_L$$

The use of photovoltaic power plants plays an important role in reducing environmental pollution, considering only their use and not the entire chain from production to recycling. By converting solar radiation energy, photovoltaic power plants are widely used as renewable energy sources. When combined with energy storage capacity, they can represent a controllable source of electrical energy.

Currently, as mentioned above, Romania has an annual solar energy potential of approximately 1400 kWh/m² in the Black Sea coastal area and southern regions, and about 1200 kWh/m² in the rest of the country.

The following table presents the average daily values for each month in the southern region of the country.

Month	Radiation*)	Month	Radiation*)
January	1,75	July	10,36
February	2,54	August	8,15
March	3,53	September	5,11
April	6,17	October	2,94
May	8,84	November	1,84
June	10,07	December	1,40
*) For horizontal surface/inclined at 35°/optimally inclined. Average annual radiation per day on a horizontal surface: 3.9 kWh/m². Average annual radiation on a horizontal surface: 1423.2 kWh/m². Average annual radiation: 162.5 W/m².			

Table 1 Average Daily Solar Radiation Values [kWh/m^2]

For maximum efficiency of photovoltaic panels and optimal use of photoelectric energy, they should be oriented so that the sun's rays strike their surface perpendicularly. Considering the sun's position and trajectory in the sky, it is necessary to adjust the orientation of the photovoltaic panels continuously.

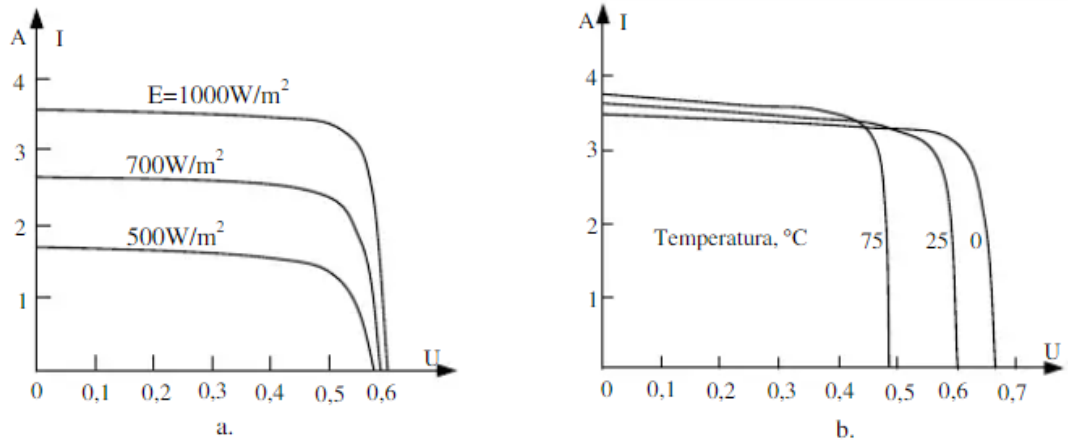
Based on measurements to date, to achieve the maximum annual energy output, photovoltaic panels are typically installed with a fixed tilt angle of 35 degrees.

Category of Photovoltaic Cells		**Efficiency [%]**	
		Experimental	Manufactured
Monocrystalline		24	16···17
Polycrystalline		17	12···13
Amorphous Cells (Thin-Film)	Silicon	12	6···7
	CIGS (Copper-Indium-Gallium-Selenide)	19	12
	CdTe (Cadmium Telluride)	16	7···10

Table 2 Efficiency of Different Types of Photovoltaic Cells

Currently, the market is dominated by monocrystalline cells due to their superior efficiency and increasingly lower production costs. They are followed by polycrystalline silicon cells, which are being improved to increase their efficiency.

According to the comparative technical data provided by the manufacturer, monocrystalline photovoltaic cells are significantly more efficient than polycrystalline photovoltaic cells. The parameters of the photovoltaic cell, depending on different levels of solar radiation and temperature changes, are as follows:



a – different levels of solar radiation b – temperature changes

Fig. 4 Influence of solar radiation on the photovoltaic cell

Photovoltaic panels are strongly influenced by solar radiation and temperature.

1.3 Active consumers (Prosumer)

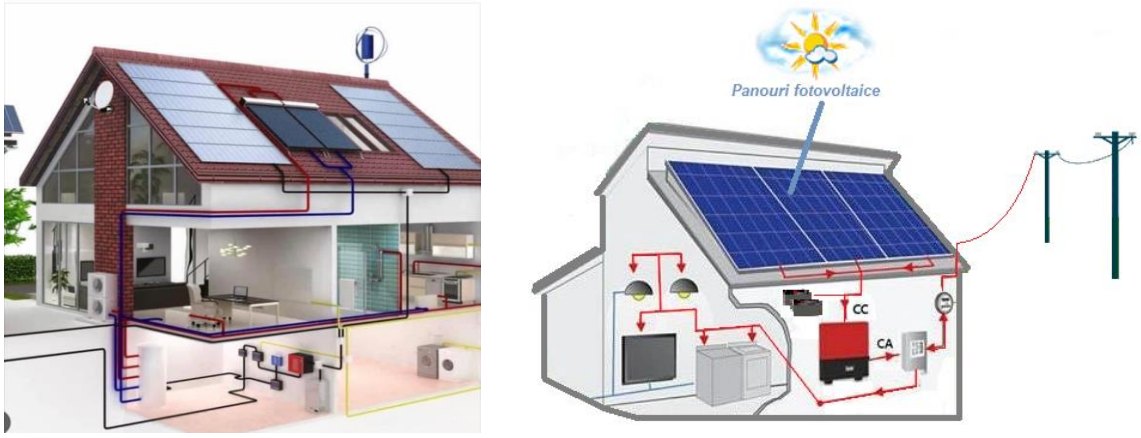


Fig. 5 Example of active consumers (prosumers)

For the economic and stable development of humanity, various forms of energy are necessary for any consumer, at affordable prices on the electricity market, taking into account the environmental impact associated with the production, transportation, distribution, and supply of electricity, as well as the recycling of equipment at the end of its lifespan.

The European Union proposes a framework for the transition to a green energy sector through a clean energy package. This provides a stable environment to stimulate investments in the field and creates new business opportunities, particularly targeting the energy industry.

The Clean Energy Package proposed by the EU places the active consumer at the center of the energy transition, enabling them to actively participate in the energy market.

In Romania, significant steps have been taken to encourage prosumers to generate electricity from renewable sources.

To enhance the use of renewable energies, the following national funding schemes are currently underway:

-The "Casa Verde Fotovoltaice" program, launched by the Ministry of the Environment, aims to implement photovoltaic systems for generating the electricity needed to cover own consumption and for injecting excess energy into the national grid. The program is administered by the Administration of the Environmental Fund.

-The "Electric Up" program, launched by the Ministry of Economy, Energy, and Business Environment, aims to implement photovoltaic systems with an installed capacity (27 kW-100 kW) designed to meet internal consumption needs and to allow the injection of excess energy into the National Energy System. The program also includes the installation of electric vehicle charging stations with an installed capacity of 22 kW.

According to Law No. 220/2008, a prosumer is defined as the final customer who owns installations for generating electricity. A prosumer has the ability to consume, store, and sell electricity generated from renewable sources (E-SRE) produced within their own property, without the production of energy being their main activity.

To ensure the adequacy and reliability of the power system with a large number of prosumers, it is appropriate to install storage systems, which will play a crucial role in both the energy system and the flexibility of consumers.

The development of advanced energy storage technologies is essential for the efficient exploitation of renewable resources. Modern batteries already provide the possibility to implement various storage solutions, positively impacting both the public electricity grid and users, especially prosumers. Technological advancements in storage systems, coupled with a significant decrease in production costs, support the integration of state-of-the-art storage systems with large storage capacities and cost efficiency into the National Energy System (SEN). It is imperative that storage installations are integrated into all energy production projects.

1.4 Hydrogen

Hydrogen is considered a simple element, but it is also the most abundant element in the universe. A hydrogen atom consists of one proton and one electron.



Fig. 6 Hydrogen Installation

On Earth, although simple and abundant, hydrogen is always combined with other elements, such as in water, which is a combination of hydrogen and oxygen. Besides its combination with other elements, hydrogen is also found in organic compounds like

natural gas, methanol, propane, gasoline, etc. Hydrogen is the lightest of elements with an atomic mass of 1.0. Liquid hydrogen has a density of 0.07 grams per cubic centimeter, water has a density of 1.0 g / cc, and gasoline is approximately 0.75 g / cc.

Advantages and Disadvantages of Hydrogen

Hydrogen stores about 2.6 times more energy per unit mass compared to gasoline; however, it requires approximately 4 times more volume for the same amount of energy. Hydrogen is not classified as a primary energy source, unlike natural gas, coal, etc. Instead, it is considered an energy carrier, often referred to as an energy vector or the fuel of the future.

Romania faces several challenges: decarbonization, environmental protection, resource conservation, creating new distributed energy sources, and energy storage. Hydrogen could be a solution for an energy-efficient economy.

Currently, hydrogen production can be achieved through industrial technologies such as:

- water electrolysis:

  $H_2O = H_2 + 1/2\ O_2$ with an efficiency of 77 %

- under chemical action:

  $CH_4 + 2\ H_2O + \text{heat} = 4H_2 + CO_2$ with an efficiency of 90 % but involves large amounts of CO2, which contribute to the greenhouse effect.

Electricity and hydrogen, as energy carriers, can be converted into each other: electricity into hydrogen through water electrolysis and hydrogen back into electricity in fuel cells. Hydrogen is also referred to as an energy carrier, with the significant advantage of being suitable for generating electricity, producing gases, and for mobility purposes.

Given the significant increase in investments in wind and solar power plants, especially in the Dobrogea region, hydrogen presents high potential for storing the electricity and transporting the energy produced by these renewable sources.

In addition to energy storage, hydrogen can be used in the following applications: residential heating systems, fuel for nuclear fusion reactors, welding, portable devices, and most importantly, in transportation such as locomotives, jet planes, ships, rockets, and vehicles.

Hydrogen offers the flexibility to address major challenges of intermittent renewable energy sources and environmental issues that will be present in Romania from 2025 to 2030. In fact, hydrogen provides access to open energy systems, and the knowledge accumulated so far confirms the feasibility of using hydrogen in both air and road transportation. Producing hydrogen in the required quantities at an affordable cost for consumers remains a challenge for the system, which can be addressed through research and innovation in this field.

Hydrogen Use in Transportation

To propel a hydrogen-powered vehicle using fuel cells, an electric motor is required. By using multiple fuel cells connected in series, the necessary power for the electric motor is provided.

Currently, several manufacturers, including Ford, Toyota, Honda, and GM, are in the testing and trial phase of powering vehicles with hydrogen fuel cells. For this, appropriate infrastructure for hydrogen refueling is necessary. This infrastructure is continuously developing, with the most advanced systems in Northern Europe and Japan.

In conclusion, hydrogen will play a significant role in the transition from conventional fuels to alternative energy sources, particularly in the transportation sector, as the number of hydrogen-powered vehicles continues to grow. However, challenges to large-scale hydrogen adoption include the required infrastructure, extraction technology, and high costs. Nonetheless, technological advancements suggest that hydrogen will become one of the main fuels in the near future.

1.5 CHEAP Tarniţa – Lapuștești, pumped storage hydroelectric power plant, essential for the SEN



Fig. 7 Example of a Pumped-Storage Hydroelectric Power Plant (PSH)

In the 2020-2030 decade, CHEAP Tarnița - Lăpuștești represents the only mature and effective large-scale energy storage system. Operating as a reversible pumped-storage hydroelectric power plant, it allows for the transfer of water between the lower Tarnița reservoir and the upper Lăpuștești reservoir.

CHEAP will have an installed capacity of 1000 MW, generated by four units, each with an installed capacity of 250 MW. The investment cost exceeds 1 billion Euros,

marking it as a greenfield investment. CHEAP will operate both as a pump and as a generator.

As the only large-scale energy storage technology, CHEAP will be used in the National Energy System (SEN) to cover peak load demands. Storing water during off-peak hours and generating electricity from stored water during peak hours is a common solution for frequency regulation in an electricity system. According to data obtained from similar plants, CHEAP's efficiency is approximately 70-85%.

Since 1975, experts within the National Energy System (SEN) have identified the need for a pumped-storage hydroelectric power plant (PSHP) as a strategic priority for SEN's development.

During this period, ISPH conducted studies and evaluated various configurations of potential PSHPs, considering the following aspects:

-The need to manage peak loads;

-Sustained growth in energy consumption;

-The potential for energy exchanges with European networks;

-The commissioning of new nuclear units at CNE Cernavodă.

CHEAP Tarnița-Lăpuștești contributes to balancing energy producers operating continuously, as well as stabilizing the National Energy System. Therefore, CHEAP holds a strategic position concerning energy security and the national protection of SEN.

According to new trends from the EU, the successful alternative to replace traditional coal-fired power plants includes pumped-storage hydroelectric plants, alongside wind and solar power plants. Traditional coal-fired plants cannot quickly respond to the intermittency of renewable energy sources, making CHEAP capable of balancing the system for periods between 4 and 6 hours.

CHEAP generates revenue from two main sources:

-By participating in the balancing market, buying energy at reduced prices to pump during the night or weekends and selling energy at competitive rates during high-demand periods;

By providing ancillary network services.

Currently, participation in the energy market can generate significant revenues for a PSHP, making the construction of such a plant economically viable, especially given that the estimated lifespan of a PSHP is between 80 and 100 years.

The strong increase in investments in renewable sources, particularly in the Dobrogea region, will stimulate greater interest in PSHPs, which provide balancing energy services.

At present, approximately 200 PSHPs are operational, with about 60 more in the project phase. In Europe, Romania is the only country without a PSHP available for the National Energy System (DEN).

1.6 Battery Storage Systems

According to data published on the websites of transmission and distribution operators, there is a strong upward trend in renewable energy sources. Since renewable energy sources fluctuate independently of demand, substantial development of storage facilities is necessary.

The National Energy System (SEN) will not be able to ensure adequacy without a balanced system of different types of sources and will necessarily require storage installations for its stabilization.

In Romania, Megalodon Storage SRL has been granted authorization and a license for a battery-based storage facility (IS Căciulați) near the 110/20 kV Căciulați electrical station, located in Moara Vlasiei, Ilfov County.



Fig. 8 Location of the storage facility

It is a premiere in the Romanian energy market as it is the first independent storage facility with a capacity of 7 MW. Another milestone of this project is that the batteries are manufactured in Romania by Prime Batteries Technology SRL.

The purpose of this storage facility is to balance the infrastructure of the Transmission and Distribution Networks (RET and RED). The battery-based storage system can be used for multiple purposes, including smoothing forecast discrepancies, balancing in electrical networks, and self-consumption.

Starting from October 2022, the storage facility was commissioned, and during November and December, it operated in various modes, including simulated fault conditions, and performance tests were conducted.

- **CONDITIONS FOR CONNECTING DISTRIBUTED GENERATION SOURCES AND STORAGE FACILITIES TO THE PUBLIC UTILITY ELECTRICAL INFRASTRUCTURE**

To connect renewable energy sources (RES) and storage installations (SI) to the public electrical grid, the process follows the regulations specified in the Electricity and Natural Gas Law No. 123/2012, as well as the rules established by the National Energy Regulatory Authority (ANRE).

This process consists of several phases, which include submitting a connection request, determining the technical solution for connection, signing the connection contract, executing the necessary works, and commissioning for commercial operation.

The solutions are determined according to ANRE regulations and are subject to approval by the relevant network operators. Additionally, the costs for issuing technical connection approvals are determined based on the methodology validated by ANRE. Moreover, the network reinforcement works required for connection are carried out by the network operator, and the associated costs are borne by the user according to the contractual terms.

For connection to the public utility electrical grid, applications and associated documentation must comply with specific regulatory provisions, and connection solutions must align with the development and investment plans of network operators, which are approved in accordance with current regulations.

- **CURRENT STATUS OF THE NATIONAL ENERGY SYSTEM (SEN) AND THE POSSIBILITY OF COVERING SYSTEM SERVICES**

The National Energy Dispatcher (DEN) is responsible for maintaining the operation of the SEN in safe conditions and in accordance with the quality standards established in the Electric Transport Network Code. DEN ensures the adequacy of the SEN through operational planning, operational scheduling, and operational control of the existing groups in the SEN with the goal of balancing production and consumption in real-time, generally using the mechanisms of the balancing market.

The dispatching of power plants in the Romanian system is complicated because the output of a particular plant can be limited by the availability of fuel; a strict merit-order approach cannot be followed. Plans are prepared daily based on minimum costs, considering the constraints imposed by fuel availability.

The SEN needs a variety of power plants, an energy mix of sources that includes both baseload generation capacities and flexible capacities to keep production and consumption of electrical energy balanced.

The use of various electricity storage technologies, including pumped storage hydropower plants (PSHP), prosumers, battery-based systems, hydrogen, and others, will lead to a partial decoupling between the consumption and production curves. This will allow peak consumption to be efficiently and economically covered with energy

generated at lower costs during periods of low consumption, including from baseload and wind power plants.

- **Types of Electricity Sources and the Evolution of Production, Consumption, and Energy Balance**

The total electricity production capacity in the National Energy System (SEN) as of 01.12.2022:

- Installed power: 18,666.33 MW

Hydropower	6641,94
Coal	3422,2
Wind	3014,91
Hydrocarbons	2629,35
Nuclear	1413
Photovoltaic	1394,1
Biomass/Biogas/Others	138,38
Geothermal	0,05
Storage installations (IS)	7,4

Table 3 Installed Power in the SEN

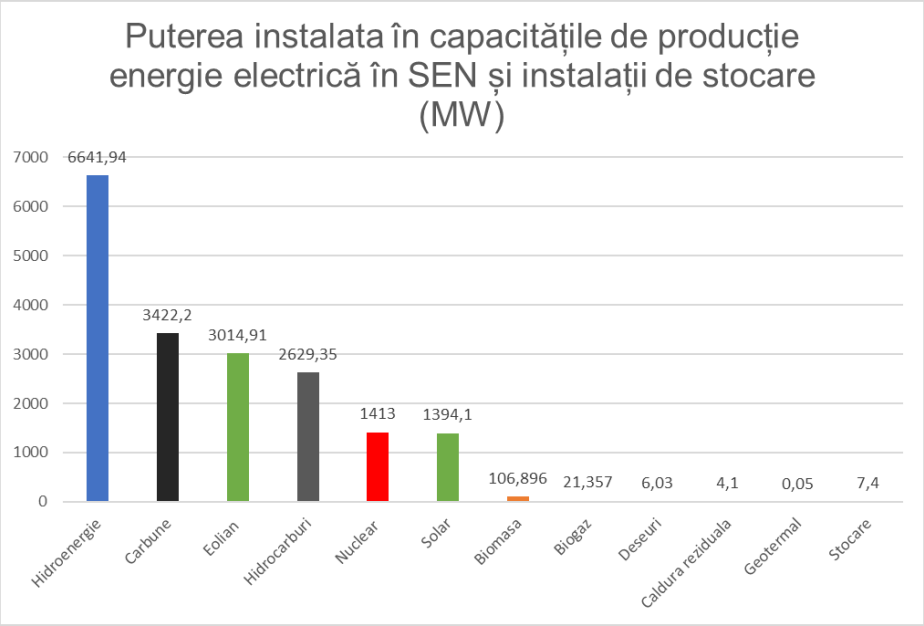


Figure 9 Installed Power in Production Capacities in the SEN and Storage Installations

The average power and electricity produced in the SEN by type of source in December 2022 were as follows:

- Hydroenergy: 1,735 MW - 1.291 TWh - 26.3%
- Hydrocarbons: 1,386 MW - 1.032 TWh - 21.0%
- Nuclear: 1,379 MW - 1.026 TWh - 20.9%
- Coal: 1,173 MW - 0.873 TWh - 17.8%
- Wind: 809 MW - 0.602 TWh - 12.3%
- Biofuels: 65 MW - 0.048 TWh - 1.0%
- Photovoltaic: 53 MW - 0.039 TWh - 0.8%

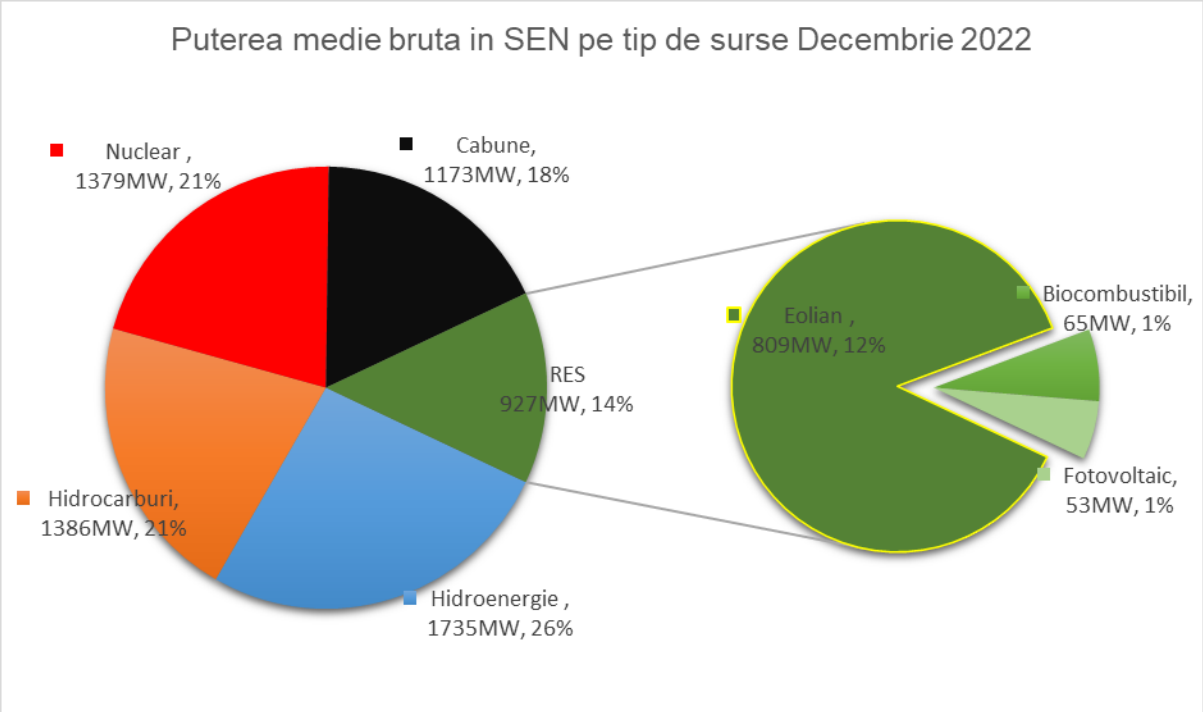


Fig. 10 Average Gross Power in SEN

Evolution of Electricity Export/Import Transactions in SEN from 2013 to 2022 Expressed in GWh and the Influence of Electricity Balance Expressed in TWh on Net Revenue Expressed in Billion Lei:

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Export GWh	7000	8200	10500	8600	6500	5400	3700	4800	5300	4800
Import GWh	1000	1300	4000	3800	3800	3000	5000	7400	7800	6000

Table 4 Evolution of Electricity Export/Import Transactions in SEN

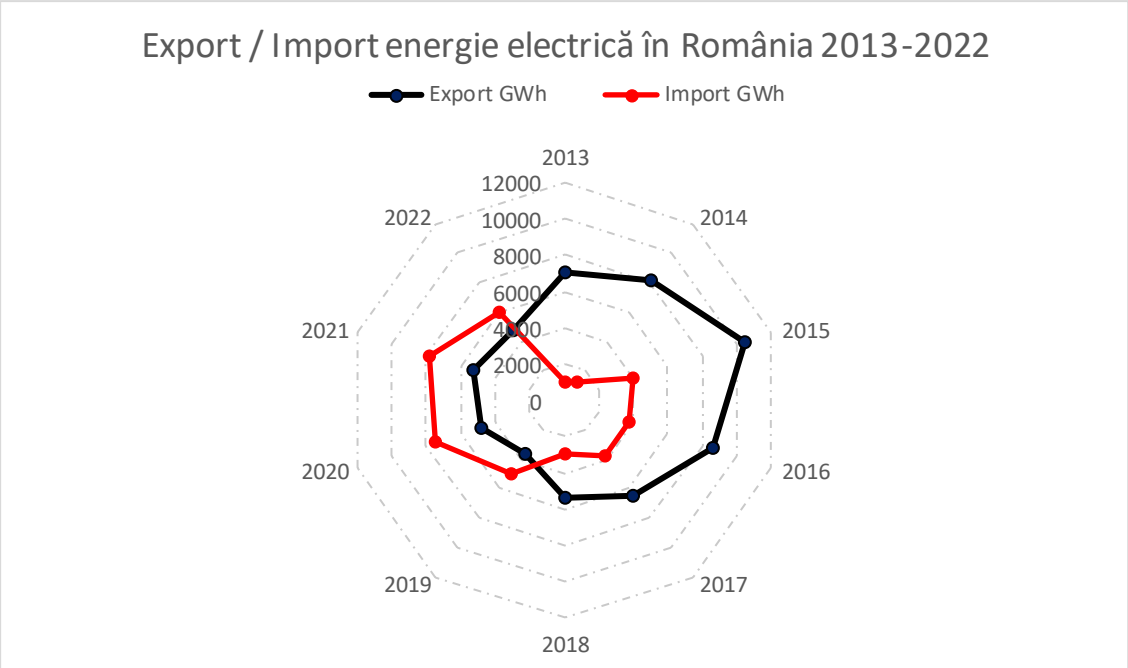


Fig. 11 Evolution of Electricity Export/Import Transactions in SEN

➢ **EU DIRECTIVES OUTLINED IN PNRR/PNIESC REGARDING RENEWABLE SOURCES AND STORAGE INSTALLATIONS**

In light of the current political and economic situation, the energy sector is undergoing significant transformation, shifting towards green energy sources. This process aims to decarbonize electrical systems, minimize greenhouse gas emissions, and encourage the use of renewable energy sources, energy storage installations, and alternative energy sources such as green hydrogen and, more recently, nuclear fusion power plants in the near future.

This shift requires consideration of the entire lifecycle—from production, transport, installation, and use, to the end-of-life and recycling of equipment that generates green energy. The ultimate goal is to ensure affordable electricity costs for the end consumer.

The question is whether Romania, through the National Recovery and Resilience Plan (PNRR), will seize the opportunity to transform its energy sector or bear the associated costs. By 2050, the EU aims to become the first continent to achieve net-zero greenhouse gas emissions.

The objective is to gradually reduce dependence on fossil fuels while emphasizing support for renewable energy sources (RES) and energy storage (ES) as well as other types of sources. This transition necessitates massive investments to build a robust and self-sufficient industry capable of providing adequate solutions to existing challenges.

By approving the National Integrated Energy and Climate Plan (PNIESC) 2021-2030, Romania has made significant strides towards the EU's proposed direction, setting a target for 2030 that 30.7% of total gross energy consumption should come from

renewable sources, with a focus on adding new renewable production capacities, approximately 7 GW.

The "Romanian Energy Strategy for the Period 2020-2030" indicates a significant level of uncertainty, especially for the year 2050. It is based on eight strategic objectives and includes a crucial national investment program. Without it, there is a risk that Europe may not achieve its ambitious goals.

Key investments of national importance included in the Romanian Energy Strategy are:

- Completion of new nuclear units;
- Construction of the Tarnița-Lăpuștești Pumped Storage Hydroelectric Power Plant (CHEAP);
- Development of the 600 MW Unit at Rovinari;
- Construction of the Turnu-Măgurele-Nicopole Hydrotechnical Complex.

The new nuclear units, alongside existing units 1 and 2, represent low-carbon emission sources and will play a central role in Romania's energy mix, thus contributing to a high level of energy independence in the region. Their installation will support the expansion of the National Energy System's production capacity with renewable energy.

As the energy mix grows with the installation of renewable energy capacities and new nuclear sources, the construction of CHEAP will ensure the flexibility of the National Energy System.

The Tarnița-Lăpuștești CHEAP is recognized as a proven solution for electricity storage, contributing to the stabilization of the National Energy System.

2. Holistic Vision on Renewable Sources, Storage Facilities, and the Possibility of Replacing Non-Renewable Sources

The European Union's targets aim to replace non-renewable energy sources, such as coal, oil, and gas, with renewable energy sources and storage facilities. Transitioning from non-renewable to renewable energy sources will help reduce greenhouse gas (GHG) emissions, thereby improving the quality of the environment we live in.

Starting from this objective, this report creates various scenarios for replacing non-renewable sources in Romania with renewable sources and storage facilities, reconsiders the future energy mixes of the National Energy System (SEN), and proposes more creative planning to achieve a transition to clean energy.

The energy shortage, particularly in European countries following Russia's invasion of Ukraine, has led many governments, including Romania's and Poland's, to focus more on short-term supply issues and less on medium- and long-term energy system planning.

Nevertheless, decision-makers in European energy systems must decide how quickly to phase out coal, how quickly to adopt renewable energy sources, and how quickly to invest in flexibility sources, alternative energy sources, and storage facilities to support broader integration of renewable energy.

Therefore, this report provides a holistic vision to imagine the contribution of renewable and non-renewable energy sources to meeting Romania's electricity needs for a smooth transition to a low-carbon economy.

The results indicate that a mix of wind systems, photovoltaic systems, and storage facilities is preferable to replace 600 MW of installed capacity in coal-fired power plants. Additionally, the case of Poland is presented, a European country with over 70% coal in its production portfolio, as it serves as a good example.

- **Integration and Optimization of Various Technologies for Reducing Carbon Emissions in Other Countries**

The gradual phase-out of coal could keep the global temperature increase below the 1.5°C threshold and help avoid climate change and health damage. According to the International Monetary Fund, $29 trillion is needed to replace coal—"46% in Asia, 18% in Europe, 13% in North America, 13% in Australia and New Zealand, 8% in Africa, and 2% in Latin America and the Caribbean."

The effects of gradually phasing out coal in European countries on meeting proposed targets have been investigated, particularly the impacts on countries that heavily export coal to Europe. Additionally, the effects on renewable energy technologies (such as wind systems, storage, and PV) believed to replace coal-fired power plants have been analyzed. Results from an econometric model showed that phasing out coal-fired power plants would have numerous positive effects on biodiversity and water management, pollution and environmental issues, and public health.

The energy transition from conventional coal-fired power plants to renewable energy-based systems was initiated through the imposition of gradually increasing carbon taxes. Subsequently, there was greater pressure from a new geopolitical crisis that began in February 2022 with the Russian invasion of Ukraine, which drove energy prices to unprecedented levels. Prices were 6-7 times higher in August 2022 on European day-ahead markets (https://euenergy.live/).

Additionally, COVID-19 put pressure on electricity prices as demand for goods surged immediately after lockdowns, leading to a higher price index. The war in Ukraine, in the Black Sea region, further stimulated demand for commodities. Furthermore, the price of renewable energy technologies and even storage has gradually decreased, and new mines discovered in Africa are enabling the development of these technologies, including batteries for electric vehicles. Photovoltaic systems have become more accessible, with the European Union offering grants and increasing energy communities and prosumers.

However, large-scale replacement of conventional vehicles with electric vehicles will transfer the pollution burden from the transport sector to the energy sector. More energy will be required to cover the load for electric vehicles; therefore, more renewable energy sources will be needed to achieve a better living environment.

This investigation is novel, and the results offer interesting perspectives for decision-makers regarding economic aspects and greenhouse gas reduction.

- **Input Data Analysis**

In the analysis, we considered open data sets recorded from January 1, 2019, to August 31, 2022. The dataset was downloaded from the TSO website and includes hourly records of total consumption, total production, and its breakdown by categories (coal, oil and gas, hydro, nuclear, wind, photovoltaic, and biomass), along with the balance of the Romanian energy system with neighboring energy systems.

The selected period covers the most recent three and a half years of hourly energy system records. This interval includes more than a year before the COVID-19 outbreak and nearly 6 months after the Russian invasion of Ukraine.

There were no significant changes in the distribution of generation sources during the studied period. Renewable energy generation is expected to slightly increase from 12% in 2019 to 15% in 2024. Additionally, coal production decreased from 22% to 17%.

- **Methods for Assessing the Potential for Replacing Non-Renewable Energy Sources (Coal, Oil, and Gas)**

To analyze the potential for replacing non-renewable energy sources in the Romanian energy system, we examined the hourly curves for the period 2019–2022. Throughout this period, non-renewable sources follow the load curve, whereas wind and photovoltaic systems do not align with the load curve. Wind generation is fairly constant, but photovoltaic generation shows a bell-shaped curve.

Nevertheless, the power needed to replace coal, oil, and gas (COG) could come nearly equally from wind and photovoltaic systems, along with storage systems that can provide energy during the evening and night hours.

The availability of wind energy, αw, is the ratio of the average available wind power (Pdw) to the installed wind power (Piw), multiplied by 100. On the other hand, the new installed power needed for wind turbines (Pinw) is the ratio of the COG power (PCOG) that needs to be replaced to the wind availability (αw), multiplied by 100.

$$\alpha^w = \frac{\overline{P_d^w}}{P_i^w} \times 100$$

$$P_i^{nw} = \frac{P_{COG}}{\alpha^w} \times 100$$

In the second scenario, if we consider replacing 50% of the non-renewable sources (coal, oil, and gas) P_{COG} cu P_i^{nw} și 50% cu P_i^{npv}, $P_i^{nw} = \frac{P_i^{nw}}{2}$ și P_i^{npv} is calculated as follows:

$$\alpha^{pv} = \frac{\overline{P_d^{pv}}}{P_i^{pv}} \times 100$$

$$P_i^{npv} = \frac{P_{COG}}{\alpha^{pv}} \times 100$$

unde α^{pv} — PV availability;
$\overline{P_d^{pv}}$ — average available PV power;
P_i^{pv} — installed power;
P_i^{npv} — newly required installed power in PV;
P_{COG} — COG power to be replaced.

The bell-shaped power curve of photovoltaic systems suggests that a generation coefficient β_h^{pv} can be calculated on an hourly basis. It is the ratio of the average available power per hour generated by photovoltaic systems $P_{d,h}^{pv}$ the installed power P_i^{pv} multiplied by 100.

$$\beta_h^{pv} = \frac{\overline{P_{d,h}^{pv}}}{P_i^{pv}} \times 100$$

$$P_{COG} = \alpha^w \times P_i^{nw} + \beta_h^{pv} \times \frac{P_i^{npv}}{100} + P_h^{bat}$$

$$P_h^{bat} = \alpha^w \times P_i^{nw} - \beta_h^{pv} \times \frac{P_i^{npv}}{100}$$

Therefore, the total power (P_{COG}) that needs to be replaced with renewable sources and storage systems is the sum of the power generated by wind turbines $\alpha^w \times P_i^{nw}$, the power generated by photovoltaic systems $\beta_h^{pv} \times (P_i^{npv})/100$, considering β_h^{pv} as in Equation (5), and storage (P_h^{bat}) which can act as a generator at night when batteries are discharged and as a consumer during the day when batteries are charged.

- **Results**

To replace 2400 MW (fossil fuels) with renewable sources or a combination of renewable sources and storage systems, the required power could be provided either solely by wind power (Scenario 1) or almost equally by wind and photovoltaic systems along with storage (as shown in Table 5) (Scenario 2). In Scenario 1, considering the above assumptions and the current availability of wind energy, the installed power required in wind turbines to replace 2400 MW of fossil fuels is approximately 8685 MW.

Table 5 Replacement of 2400 MW of Fossil Fuels (Coal, Oil, and Gas)

2400 MW Replace	Pi Eolian [MW]	Pi Fotovoltaic [MW]	IS [MW]
Scenariu1	8685	0	0
Scenariu2	4342.5	4089.3	15,486

In the second scenario, if the installed capacity in wind turbines were 4342.5 MW, the power generated by wind turbines could be around 1200 MW. Therefore, the storage requirements are shown in Fig. 12.

The hourly storage requirements for nighttime would be 1200 MW, which, together with the 1200 MW from wind turbines, could replace the 2400 MW currently generated by non-renewable fossil fuel sources. However, the required capacity for battery systems is very high and very costly in this scenario. Thus, the total capacity needed to replace 2400 MW of non-renewable fossil fuel sources exceeds 15,000 MW.

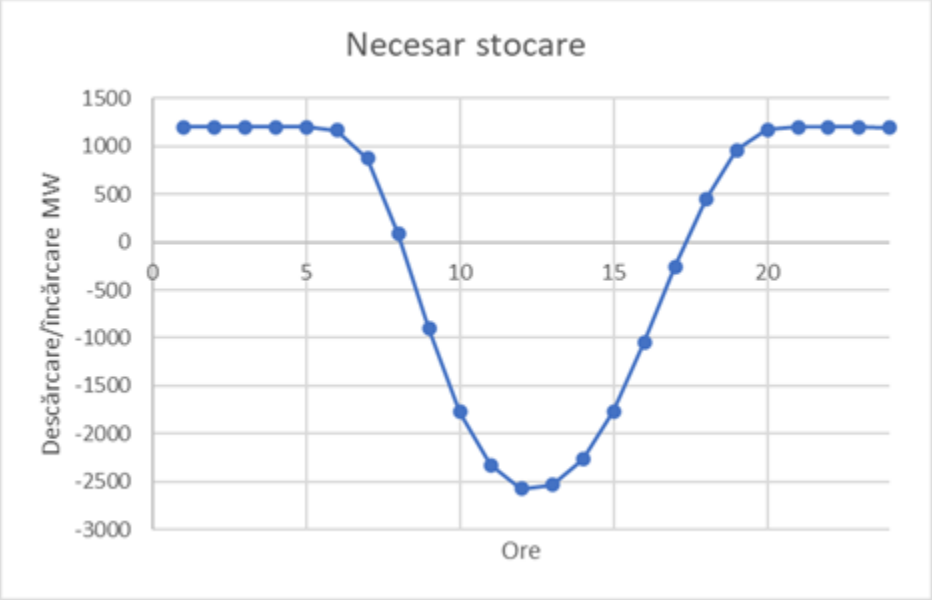


Fig. 12 Storage requirements for replacing 2400 MW of non-renewable fossil fuel sources (COG).

Therefore, the target should be reduced; for example, instead of replacing 2400 MW, we could consider a more feasible capacity such as 600 MW.

Initially, we can aim to replace 600 MW generated by coal-fired power plants with wind, photovoltaic, and storage systems.

However, combined cycle gas units produce 41.19% of GHG emissions per MWh compared to coal-fired generating units.

Therefore, it is preferable to replace coal first.

In this context, the first scenario requires approximately 2200 MW of newly installed wind capacity (CEE), while the second scenario involves around 1100 MW of wind (CEE), 1022 MW of photovoltaic (CEF), and 3900 MW of storage (as shown in Table 6).

Table 6 Replacement of 600 MW of non-renewable fossil fuel sources (COG).

600 MW Replace	Pi Eolian [MW]	Pi Fotovoltaic [MW]	IS [MW]
Scenariu1	2171.25	0	0
Scenariu2	1085.62	1022.32	3871.50

The total cost of storage, if based on batteries, will be around 1.9 billion EUR, given that the cost is 500,000 EUR per MW.

In the first scenario, where approximately 2400 MW is replaced, an average of 1.69 million tons of CO2 is avoided, whereas in the second scenario, 1.09 million tons of CO2 are avoided.

For the calculations, it is assumed that gas-fired plants produce 407.32 tons of CO2 per MWh, while coal-fired plants produce 988.83 tons of CO2 per MWh.

Additionally, in this replacement scenario, the coal industry will not be immediately affected, and the transition is therefore slower.

Some studies suggest that photovoltaic plants are much more suitable than wind for replacing jobs in coal mining; therefore, a combination of wind and photovoltaic systems could be better. In South Africa, the effects of decarbonization on the energy system and the implications for employment in the labor market are extensively discussed.

Even in the second scenario, with a 600 MW replacement, the costs are very high. However, other storage options can be explored, such as consumer/community flexibility and small hydro projects with storage capacity.

3. Connecting Storage Systems to the Public Electrical Grid

The calculations performed in this case study were conducted in accordance with the requirements of the Transmission Network Code (RET) and the regulations set forth by the National Regulatory Authority for Energy (ANRE).

The case study complies with the rules established for developing scenarios, fundamental average regimes, and sizing regimes used in studies for connecting new power plants or units, as per the rules and instructions provided by the Transmission System Operator (TSO).

The purpose of the case study was to assess the connection of the Tarnița 1000 MW Pumped Storage Hydropower Plant (CHEAP) and a 1000 MW Freeflow Battery Storage System (IS) to the National Energy System (SEN), considering the specific characteristics of these types of plants.

Based on the Base Load Regimes (RMB) corresponding to the following periods: Morning Peak Summer (VDV), Night Off-Peak Summer (GNV), Evening Peak Winter (VSI), and Morning Peak Winter (VDI), provided by CNTEE Transelectrica SA, we analyzed the impact of connecting storage systems to the SEN.

In addition to the aspects already highlighted, the case study emphasizes the potential functionality of Renewable Energy Sources (RES) that could be integrated into the storage infrastructure, along with an assessment of the storage system's capacity to contribute to voltage regulation in the region.

The case study presents and analyzes two storage systems:

- Tarnița 1000 MW Pumped Storage Hydropower Plant (CHEAP) is located in the North-West of the country, in section S4, which is a deficient area with low power flows in the Transmission Network Code (RET).
- The Freeflow 1000 MW Battery Storage System (IS) is located in the South-East of the country, in section S6, which is an area with a significant surplus. Installing storage systems that charge when there is an excess of renewable energy can reduce the need for reinforcements in the RET.

These plants are situated in diametrically opposite corners of the National Energy System (SEN): different sections with either power deficits or surpluses. However, both aim to ensure the adequacy of the SEN according to the specific characteristics of these types of plants.

In both areas, S4 and S6, the connection of multiple Conventional Power Plants (CEF) and Renewable Energy Sources (RES) is planned. Connecting these sources will require development work by the Transmission System Operator (TSO) and Distribution Operator (DO).

The following assumptions were considered, based on data provided by the TSO as well as data from various battery storage equipment manufacturers:

For the Tarnița 1000 MW Pumped Storage Hydropower Plant (CHEAP):

- Installed Capacity: The Tarnița Pumped Storage Hydropower Plant has an installed capacity of 1000 MW, achieved with 4 reversible units of 250 MW each. These units operate in two modes:
  - During Peak Consumption in the National Energy System (SEN): The units will operate as generators, producing and delivering power to the Transmission Network (RET).
  - During Low Consumption in SEN: The units will function in pump mode, using electrical energy to refill the storage reservoir.
- Characteristics of the 4 Units:

  - Apparent Power: 280 MVA at a power factor (cos φ) of 0.9

- Power Produced in Generator Mode: 256 MW
- Power Consumed in Pump Mode: 270 MW
- Direct Reactance:
- Transversal: 0.85 to 1 pu
- Longitudinal: 0.43 to 0.5 pu
- Transient Reactance:
- Transversal: 0.2 to 0.3 pu
- Subtransient Reactance:
- Transversal: 0.23 to 0.26 pu
- Longitudinal: 0.18 to 0.20 pu
- Connection: Each unit is connected via a 280 MVA transformer block, 400/15.75 kV, with a short-circuit voltage (Uk) of 11%.

For the Freeflow Battery Storage Facility:

The Freeflow Battery Storage Park is an independent facility with an installed capacity of 1000 MW. The technical solution chosen involves equipment from Hitachi, for which we requested technical datasheets.
The proposed technical solution is based on the following equipment:

- CATL Batteries: 5334 battery racks, each rack with a power of 375 kW
- Hitachi PS 1000 Power Converters: 667 inverters with a power of 1.5 MW each
- Transformers 0.69/20 kV 7.5 MVA: 148 units
- Substation 400 and 20 kV
- Power Transformers 280 MVA, 20/400 kV: 4 units

Results of Steady-State Calculations With and Without Considering the Storage:

Without Considering CHEAP:

The S4 section is an area with low power flow values in the RET. In the RED (Energy Distribution Network), the connection of multiple CEF (Electricity Generation Facilities) is planned, requiring development work at the Distribution Operator (OD).

Without the CEFs being connected, the area remains deficient at peak load, necessitating the connection of power plants that can cover consumption and/or export requirements.

Without Considering IS Freeflow:

From the analysis conducted to check operating conditions under certain criteria, it was found that there are several overloads that would require network reinforcements, especially in the RET (Electricity Transmission Network).

The S6 section is a heavily surplus area, and installing storage facilities that can charge when there is an excess from renewable sources could reduce the number of reinforcements needed in the RET.

- With CHEAP Considered in Generator Mode, at the SEN Peak Load Level:

In operating conditions, no overloads on RET elements or exceedances of permissible voltage bands were observed.

- With CHEAP Considered in Pumping Mode, at the SEN Low Load Level:

In operating conditions, no overloads on RET elements or exceedances of permissible voltage bands were observed, provided that the reinforcements outlined in the development plan are implemented (such as the 400kV Suceava–Gădălin PIF 2030 line or upgrading the West axis to 400kV, etc.).

- With IS Freeflow Considered:

The inclusion of IS in the Gura Ialomiței station leads to lower loadings in the RET and eliminates the overload observed on the 400kV Gutinaș–Brașov line. Replacing the conductor on the 400kV line has a cost of approximately €15 million.

The electrical transmission network is required to ensure a static stability reserve of at least 20% and 8% in both operating modes of the system.

When CHEAP Tarnița operates in generator mode:

Analysis of voltage stability for section S4 shows that power evacuation from section S4 occurs with normative stability conditions (a reserve greater than 20%, respectively 8%) for medium-term analysis.

When CHEAP Tarnița operates in pumping mode:

Analysis of voltage stability for section S4 shows that the analyzed area can absorb power under normative stability conditions (a reserve greater than 20%, respectively 8%).

For IS Freeflow:

Analysis of voltage stability for section S6 indicates that power evacuation from section S6 occurs under normative stability conditions for N elements in operation (a reserve greater than 20%).

Transient stability conditions and critical time determination reveal that operation in pumping mode with all four units leads to the shortest critical times for fault clearing (85 ms).

In the case study, the participation in voltage regulation in the area was analyzed and the following results were obtained:

- CHEAP Tarnița can contribute significantly to voltage regulation (up to approximately 20 kV) in both operating modes: generator and pump.

- In both situations, considering a fixed transformation ratio of 15.75/400 kV for the step-up transformers, the reactive power available from the four units is not fully utilized.

At the execution stage, after receiving the exact data for the future reversible units that will be installed at CHEAP Tarnița, the optimal value for the nominal transformation ratio will be established, as well as its range of variation (number of taps, voltage variation per tap, etc.).

The calculation of short-circuit currents highlights that the presence of the two storage installations (CHEAP Tarnița and IS Freeflow) influences the short-circuit stress values at nearby nodes, without exceeding the threshold values at these nodes (31.5 kV):

- At the Gădălin 400 kV node, Ik3 increases from 11.03 kA to 17.08 kA (54.8%).
- At the Mintia 400 kV node, Ik3 increases from 13.58 kA to 18.32 kA (34.9%).

The requirements necessary for the two storage installations to ensure, at the connection or delimitation point, compliance with European standards and ANRE Order No. 12/2016, are presented. This ensures that the quality indicators of the electricity are within the limits established by these standards.

The safety indicators were calculated at the delimitation point and resulted in a high level of safety, considering that the new 400 kV stations are equipped with double bus systems and advanced equipment, and there is capacity reserved in the power evacuation paths for CHEAP Tarnița and IS Freeflow.

Regarding the total investment cost for CHEAP Tarnița, it amounts to over 1.2 billion Euros, of which the necessary works for connection to the transmission network, the electrical station, and transmission lines amount to 166.15 million Euros.

For IS Freeflow, the total cost will be around 0.4 billion Euros, with additional works for connection to the transmission network, the electrical station, and the transmission line amounting to 20.43 million Euros.

In the subsequent design phases, the total investment costs for CHEAP Tarnița and IS Freeflow will be determined based on preliminary measurements and general/object estimates in accordance with HG 907/2016.

As battery storage technology continues to develop, there is potential for these prices to decrease, making it feasible for each consumption or production point to be equipped with an energy storage system using batteries.

4. Integration of Storage Installations with Users in the Presence of Photovoltaic Systems

One of the solutions proposed by the European Union for a future with lower carbon emissions and increased independence from fossil fuels is to provide consumers with an active role in the energy transition process, enabling them to become active

consumers (prosumers). The EU has assigned new roles and responsibilities to active consumers to coordinate the generation and use of electricity, seeing this as an opportunity for sustainable development for future generations. This paper presents the advantages and disadvantages of becoming an active consumer based on grid connection.

The aim of this paper is to analyze the electricity production/consumption and the storage requirements for two typical photovoltaic installations, considering one user as an active consumer with an on-grid connection and another as an off-grid consumer equipped with a battery-based storage system:

- Active consumer from the Bucharest area (prosumer, on-grid connection).
- Residential consumer from the Călărași area (consumer, off-grid connection), who has both a photovoltaic installation and a battery storage system.

The paper is based on existing data obtained from household sources, inverter data, prices from various manufacturers and suppliers, accumulated technical knowledge, and experience in the national power sector, which is continuously evolving and developing.

We analyzed the operating characteristics of photovoltaic panels and storage systems for both types of users within the analyzed intervals and created reasonable hypotheses based on the type of grid connection and off-grid status. By identifying the main load recipients of the consumers, we were able to establish their daily load curve. For each typical photovoltaic installation, using data from the inverter, we determined the associated electricity production and consumption.

We analyzed the storage requirements overlaying the evolution of electricity generation and use. To support traditional consumers in becoming active consumers, Romania launched its own funding program for this purpose while implementing European legislation. The components of photovoltaic installations and storage systems for both users with different grid connections were analyzed.

The paper examines the management of production, consumption, and electricity storage for the two consumers with photovoltaic installations but different grid connections, on-grid and off-grid. August was chosen as the analysis period, allowing for a comparison between the two types of grid connections.

For the active consumer with an on-grid connection, it was found that the sale price of surplus energy is considerably lower compared to the cost of energy purchased from the grid. This represents a disadvantage for the active consumer.

It would be beneficial if, through government programs aimed at promoting renewable energy, active consumers were equipped with a storage system (IS) to manage the energy produced in the afternoon so that it could also be used during the evening and night.

For the year 2030, there is an anticipated increase in electricity usage, potentially doubling, particularly in the road/transport sector, the expansion of 5G networks, and the high number of residential consumer devices. Therefore, developing new and advanced capacities is essential.

With a significant number of active consumers, there is potential for network congestion and the need to address network imbalances, especially at off-grid (OD)

locations. Thus, it would be beneficial for new connections to include a share of storage, a solution also applicable to connecting renewable sources to public interest electric grids managed by the Transmission System Operator (TSO).

Beyond active consumers, the entire energy system requires storage installations, including large-scale storage systems such as pumped hydro storage (CHEAP).

As battery storage systems become more accessible, they offer the best solution for managing electricity consumption, regardless of grid connection mode. For off-grid connections, this management is even more evident, smoothing evening consumption peaks.

The results provide valuable insights for decision-makers considering becoming active consumers (prosumers). The findings demonstrated the feasibility of storage installations and highlighted the importance of optimizing consumption through various technologies, such as smart plugs with Wi-Fi and smartphone applications. With these smart devices, active consumers can optimize their consumption by smoothing out evening peaks.

By shifting consumption away from evening peaks, active consumers can utilize the entire amount of renewable energy produced and achieve a significantly lower total energy cost, as the amount of energy purchased from the supplier will be much reduced. It is evident that there is a correlation between the energy purchased from the supplier and the load curve of the active consumer.

Smoothing out consumption peaks and filling in gaps will lead to a more even load on the electric grid, potentially deferring new investments.

From the above analysis, battery storage systems offer far more benefits than disadvantages to users with photovoltaic installations, regardless of their grid connection.

Advantages of Battery Storage Systems for Residential Use:

- Energy Independence
- Smoothing of Consumption Peaks and Load Shifting
- Backup Power
- Optimized Energy Consumption
- Support for the Electrical Grid
- Positive Environmental Impact
- Financial Benefits
- Increased System Resilience
- Integration of Renewable Energy
- Technological Advancements in Storage Systems

Disadvantages of Battery Storage Systems for Residential Use:

Initial Cost

- Limited Lifespan
- Dependency on Manufacturing Resources
- Space Requirements
- Safety Concerns, Fire Risk
- Inadequate Recycling at End of Life

FINAL CONCLUSIONS AND PERSPECTIVES

General Conclusions

Recently, climate change has been at the forefront of global discussions. The European Union has profoundly transformed its approach to the production, trading, and consumption of electricity by adopting ambitious policies aimed at reducing greenhouse gas emissions (GHG) and liberalizing markets. Amid an unprecedented energy transition across the European continent, it is crucial for EU actions to ensure a constant supply of energy for consumers, reduce CO2 emissions, promote the generation of energy from renewable sources, facilitate the creation of a pan-European energy market, enhance energy efficiency, and advance the development of electricity storage technologies.

Renewable energy sources have become a major focus of development worldwide, driven by the EU directive to support the reduction of GHG emissions and increase electricity usage through the introduction of electric transportation means.

Intensive efforts to limit environmental pollution, the current political and economic context, and the need to ensure the adequacy of the national electricity system have led to the increasing development and use of renewable energy sources and the expansion of energy storage capacities.

The EU directive on renewable energy has stimulated a heightened interest among member states in developing renewable energy sources, with particular emphasis on wind and solar power.

The production of energy from wind and solar power is intermittent throughout the year and cannot be regulated in the same way as traditional power plants. To ensure adequate energy supply, it is essential to have available production capacity in traditional plants that can be quickly activated or in energy storage systems.

Recently, the national electricity system has undergone changes in its production structure to quickly adapt and accommodate a broader range of renewable energy sources, including energy storage installations.

Romania benefits from a wide and abundant range of renewable energy sources, including biomass, hydroelectric power, geothermal potential, as well as vast potential for wind and solar (photovoltaic) energy.

The mix of renewable sources and the integration of storage systems represent a major challenge for the operation and stability of the National Electricity System (SEN) due to their variable nature. The intermittent character of these sources can threaten the stability of the electricity system, as well as their decentralized and geographically dispersed nature.

In contrast to traditional power plants, which are large sources of power with well-dispatched locations and capacities, and contribute to frequency and voltage regulation in electrical grids, the integration of renewable sources into SEN introduces significant uncertainty regarding whether the system is prepared to cover power deficits when these sources are not injecting into the grid.

Although the future belongs to renewable resources, the ability to store electrical energy will constitute a major challenge for maintaining a balanced and efficient electricity system.

Storage systems will aid the balancing market by "smoothing out peaks" in the Day-Ahead Market (PZU), a market in Romania that is still in its early stages of organization and operation.

The optimal integration and functioning of storage systems in SEN aim to:

- Cover the technological consumption of network operators.
- Ensure the adequacy of SEN.
- Support the electricity balancing market by "smoothing out peaks" in PZU.
- Store electrical energy in areas with a high concentration of renewable resources, such as wind and photovoltaic.
- Stabilize the electrical grid by providing frequency regulation services.
- Play a key role between the production and consumption of electricity.
- Contribute to a more sustainable planet through a harmonized energy system, ready to include a greater diversity of renewable sources, thereby increasing system flexibility.
- Optimize energy use.
- Conserve the environment and reduce GHG emissions.
- Promote innovation/advancements in research and development and competitiveness in the field of energy storage and its utilization when the system requires it.
- Enhance consumer flexibility.
- Reduce imbalances in real-time operation.
- Shorten the payback period for investments in the National Energy System.
- Improve energy autonomy for users across different levels within the electrical networks.

A complete transition to energy exclusively from renewable sources and storage systems involves significant economic costs that will be reflected in consumer bills. Therefore, it is essential to understand in detail the entire energy chain from production to consumption, based on an appropriate set of regulatory norms to encourage the use of renewable energy sources and storage systems.

Ultimately, energy storage plays a crucial role in ensuring the adequacy of SEN by maintaining the quality of electricity, reliability, and efficiency of the system. The essential role of storage systems is to level the production curve of energy from variable sources. Implementing electricity storage systems requires the use of efficient, safe, and viable technologies.

Personal Contributions

The research paper titled “Integration and Optimal Operation of Storage Systems in the National Energy System in the Presence of Renewable Sources” addresses a critical need within the national electricity system, which is increasingly challenged by the growing demand for electricity due to the ongoing development of human society.

This research aims to study and develop optimal solutions for the integration and optimal operation of electricity storage systems within the national electricity system.

The paper tackles a current and significant topic—energy storage—which has been, is, and will continue to be a key objective for the development of human society.

The doctoral dissertation is organized into four key chapters, framed by an introduction and a final chapter that includes conclusions, personal contributions, fundamental concepts, and essential provisions. The document includes lists of figures, tables, and abbreviations, as well as a bibliography of references used. Additionally, a list of the author's publications from the doctoral studies period is provided at the end of the document.

The initial chapter focuses on theoretical aspects of renewable energy sources and storage systems within the National Energy System (SEN), analyzing their structure, operation, and development, as well as the challenges associated with integrating them into the grid.

In this chapter, the current state of SEN and the potential for covering system services are presented, highlighting the system's continuous evolution and new approaches to types of electricity sources. It includes an analysis of the evolution of production, consumption, and balance within SEN, as well as the average electricity price on the Day-Ahead Market (PZU) and an assessment of greenhouse gas (GHG) emissions. The chapter concludes with an overview of the targets set by the EU through the National Recovery and Resilience Plan (PNRR) and the National Strategy for Energy and Climate (PNIESC) concerning renewable sources and storage systems.

The second chapter provides a holistic view of renewable sources, storage systems, and the potential replacement of non-renewable sources such as coal, oil, and gas. It also analyzes the integration and optimization of various technologies for reducing carbon emissions in other countries, specifically methods for replacing non-renewable energy sources (COG).

It was found that Polish experience could be highly beneficial for Romania. Poland offers a framework for the growth of energy communities, encouraging the development of energy clusters with new regulations and business models where value sharing is crucial, as it ensures the growth and stability of energy communities. Similar steps should be followed in Romania to form consumer coalitions and encourage community development, making their members less affected by energy poverty and geopolitical instability.

Chapter three (case study) details the possibilities of connecting two storage systems to the electrical grid: a pumped storage hydroelectric power plant (CHEAP Tarniţa 1000 MW) and a battery-based storage system (IS Freeflow 1000 MW), considering the specific characteristics of these types of plants. The chapter examines the impact of their connection on the Transmission Network and potential limitations that the network might impose on these storage systems. It concludes with a summary of the results obtained from the case study, which assessed the effectiveness of introducing a storage system into the Transmission Network and its impact on the balancing market.

Chapter four aims to analyze electricity production/consumption and storage requirements for two typical photovoltaic installations with an active grid-connected consumer and an off-grid residential consumer equipped with a battery-based storage system:

- An active consumer in the Bucharest area (prosumer, grid-connected).

- A residential consumer in the Călărași area (traditional consumer, off-grid connection), who also has a photovoltaic system and a battery-based storage system.

The paper is based on existing data obtained from personal households, inverter data, prices from various producers and suppliers, technical knowledge accumulated over time, and experience gained in the national electricity sector, which is continuously evolving.

The operational characteristics of photovoltaic panels and storage systems at the two user levels were analyzed during the studied intervals, and reasonable hypotheses were created considering the type of grid and off-grid connections.

The results provided valuable insights for decision-makers regarding the possibility of becoming an active consumer (prosumer). The findings demonstrated the feasibility of storage systems and the importance of optimizing consumption through various technologies, including smart plugs using Wi-Fi and smartphone applications. These intelligent devices allow active consumers to optimize their consumption by smoothing out evening consumption peaks.

By shifting consumption away from evening peaks, active consumers can use the entire amount of generated renewable energy and achieve a significantly lower total energy cost, as the amount of energy purchased from the supplier will be reduced. It is evident that there is a correlation between the energy purchased from the supplier and the load curve of the active consumer.

The final part of this project is dedicated to concluding remarks, personal contributions, and future development perspectives.

Future Development Perspectives

This scientific research paper provides a series of contributions concerning the integration and optimal operation of storage systems within the national energy system, with implications for the balancing market. It is based on concrete data obtained from the Romanian electrical system, highlighting my commitment to conducting studies with direct applicability in the country.

This doctoral thesis represents a continuation of my ongoing concerns and will lead to exceptionally useful results for the electrical system. The theoretical aspects addressed, along with the practical applications that can be developed, have given the proposed study significant scientific value and opportunities to advance current knowledge.

As future research and development perspectives, I have proposed the following:

- Integration of Artificial Intelligence (AI) into a system with photovoltaic panels and battery storage at a household level. AI can improve the performance, efficiency, and overall reliability of the analyzed system.
- Incorporation of the on-grid photovoltaic system into an energy community.
- Acquisition of a monitoring system for the off-grid photovoltaic system.

- Development of a graphical representation application for the sources used in the National Energy System (SEN) as well as the current status of SEN.
- Development of an application to monitor and forecast the power output of the photovoltaic installations.

In analyzing the challenges facing the national electrical system, I aim to address the following current issues within SEN:

- The low consumption of electricity coupled with large amounts of renewable energy creates an imbalance in SEN adequacy.
- Prosumers need to have energy storage capacities to balance the production and consumption of electricity produced in the afternoon, which can then be used during the evening and night.
- Losses and imbalances caused by active consumers as well as voltage regulation issues in their inverters.
- In 2023, the first independent storage installation with a capacity of 7 MW was established, whereas the SEN, based on sizing calculations, needs a mature storage installation such as CHEAP Tarnița.
- The reduction in electricity production from coal without being balanced by other sources.
- The installed capacity, according to the ANRE website, is approximately 18,500 MWh of production; however, many of these are not able to participate in balancing production and consumption or no longer exist.
- The judicious placement of electricity production resources: all production capacities, except for the units at Iernut, are located in the southern part of the country, and supplying consumers in the north and east involves long distances across the electrical networks, leading to significant losses.
- The age of electrical networks, which raises uncertainty about whether the infrastructure will withstand the growth in consumption over the coming decades.

Furthermore, Romania benefits from a varied and stable energy mix, ensuring the proper functioning of the National Energy System (SEN). However, progress in the energy sector is closely linked to the implementation of investment projects in the country’s energy infrastructure.

Research and development are ongoing in battery storage technology. This technology continues to advance, and storage systems remain a challenge for the electrical system.

LIST OF PUBLICATIONS

- *Data Analytics for the Transmission System Operators – Database Systems Journal* – dbjournal.ro - București 2020. Authors Dan PREOȚESCU, Simona-Vasilica OPREA, Adela BÂRA, Niculae OPREA , Osman Bülent TÖR.
- *Machine learning in electricity fraud detection in smart grids with multivariate Gaussian distribution* – Sciendo.com/article 2021 - Authors Simona-Vasilica OPREA, Adela BÂRA, Niculae OPREA.
- *How fast to avoid CO_2 emissions. A holistic view on the RES, storage and non-RES replacement in Romania* – article Environment Research and Public Health – mdpi.com 2023 - Authors Niculae OPREA, Simona-Vasilica OPREA, Adela BÂRA.
- *Electricity Price Evolution and the Disruptive Economic and Geopolitical Context on the Spot Market. A Romanian Case Study* – article BASIQ 2023 International Conference on New Trends in Sustainable and Consumption – Authors Niculae OPREA, Simona-Vasilica OPREA, Adela BÂRA.
- *Big Data Management and NoSQL Databases* – article "Ovidius" University Annals, Economic Sciences Series, Volume XXIII, Issue 1 /2023 – Authors Simona-Vasilica OPREA, Adela BÂRA, Niculae OPREA.
- *Trading in the Quantum Era: Optimizing Bitcoin Gains and Energy Costs* – Authors Simona-Vasilica Oprea, Adela Bâra, Cristian Bucur, Bogdan-George Tudorică, Niculae Oprea.
- *Integration of storage installations at prosumers in the presence of photovoltaic installations, Scientific Bulletin of the Politehnica University of Bucharest 2024 – Authors Niculae Oprea, Radu Porumb.*