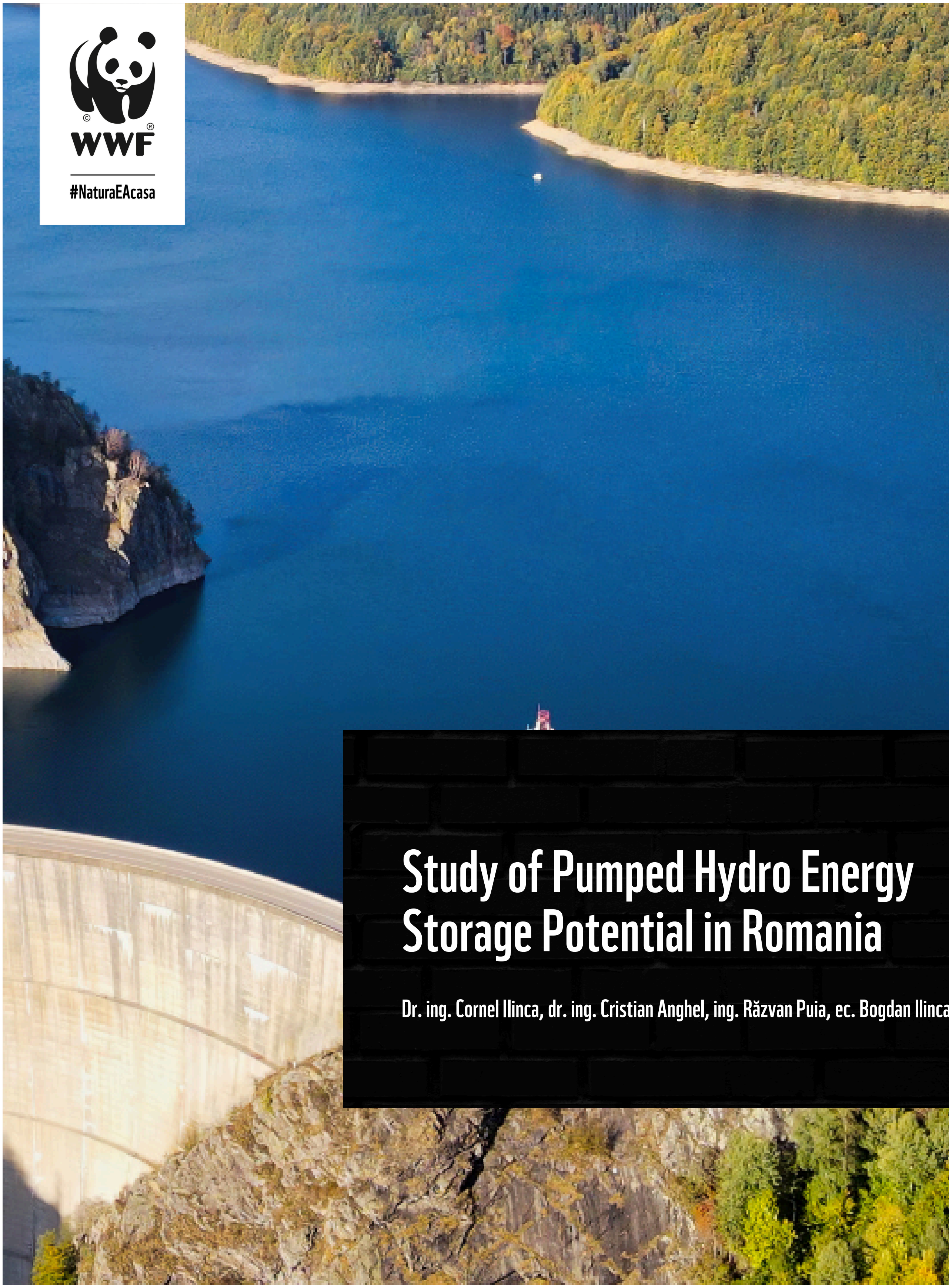

#NaturaEAcasa

Study of Pumped Hydro Energy Storage Potential in Romania

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NOMENCLATURE

PHES - Pumped Hydro Storage

PHSIF - Pumped Hydro Storage International Forum

IHA - International Hydropower Association

EIAs - Environmental Impact Assessments

CBA - Cost-benefit analysis

NES - National Energy System

NNR - Normal retention level

NmE - Minimum level of exploitation

Executive Summary

Pumped Hydro Energy Storage (PHES) is a solution for balancing Romania's National Energy System (NES), enabling greater integration of renewable energy sources such as wind and solar. With increasing demand for energy storage at both European and national levels, PHES offers a mature and efficient method to enhance grid stability, energy security, and the transition toward a low-carbon economy.

Romania has identified ten potential locations for PHES projects, with a combined capacity exceeding 2,000 MW.

PHES enables energy shifting from off-peak to peak demand, enhancing system resilience and supporting black start capabilities crucial for grid recovery in case of large-scale outages. While initial capital costs are high, the long-term economic, environmental, and social benefits outweigh the investments.

The Frasin-Pângărați project, with a capacity of 300 MW, an investment of €300 million, and a projected payback period of 11.2 years, is a promising option that benefits from existing hydrotechnical infrastructure, minimizing environmental disruption. The Tarnița-Lăpuștești project was initially planned for 1,000 MW but faces economic and environmental risks, with a recommendation to scale it down to 300 MW. The Colibița project, with a capacity of 200 MW, is cost-effective and well-integrated into the NES but is situated in a Natura 2000 site, requiring careful ecological mitigation. The Socol project, originally planned for 1,000 MW, was reduced to 250 MW due to economic and environmental constraints but remains its location in the Iron Gates Natural Park remains an important issue. The Oașa Lake sites—Girbova, Plesi, and Cugir—have a combined capacity of 900 MW and are technically feasible but pose major financial and ecological challenges. The Siriu project, with a capacity of 300 MW, has significant hydro-pumping potential but is constrained by high costs, geological instability, and biodiversity risks. The Simian and Poiana Mărului projects, both located in Natura 2000 sites, raise concerns over ecological damage and require careful assessment.

While PHES contributes to climate change mitigation by supporting renewables and reducing fossil fuel dependence, it poses grave environmental challenges. The construction phase may

lead to deforestation, habitat disruption, and biodiversity loss. The creation of reservoirs can alter hydrology, affecting water availability and aquatic ecosystems, and organic matter decomposition may generate methane emissions.

To mitigate these impacts, PHES projects must be strategically located away from protected areas such as Natura 2000 sites, with detailed site selection studies ensuring minimal ecological disruption. The study assessed potential locations, prioritizing those with existing infrastructure to reduce environmental impact. For example, Frasin-Pângărați was identified as having minimal ecological risks, while other locations require additional safeguards. Proper water management strategies will prevent excessive withdrawals affecting downstream ecosystems. Additionally, implementing reforestation, erosion control, and habitat restoration programs can help offset land degradation.

Beyond biodiversity concerns, PHES projects can impact local communities through land-use changes and water level fluctuations. Transparent stakeholder engagement, fair compensation policies, and adaptive management strategies are essential for maintaining social acceptance and ensuring a fair balance between energy security and environmental protection.

To maximize PHES benefits, Romania should prioritize PHES in its national energy strategy, leveraging EU funding sources. Optimizing project design through automation, digitalization, and real-time energy management systems will enhance efficiency. Integrating PHES with complementary storage solutions, such as high-capacity batteries and green hydrogen, will help maintain a balanced energy mix. Encouraging distributed PHES facilities (<300 MW) will improve grid flexibility while reducing financial and environmental risks.

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1. Global overview of Pumped Hydro Energy Storage

Pumped hydro storage power plants (open or closed loop) are hydroelectric power plants aimed at generating additional electricity. The concept of such plants is to pump the reservoir from a lower level to a higher level and then, when needed, release that volume of water back into the lower reservoir. The water is pumped into the upper reservoir during off-peak hours when electricity prices are low and released into the lower reservoir during peak hours when electricity prices are high, resulting in an economic gain. Thus, Pumped Hydro Energy Storage (PHES) power plants aim to exploit the price difference between storing and generating electricity [1].

PHES is a mature technology offering a reliable and efficient solution for storing large amounts of energy.

PHES systems play a crucial role in grid stability, especially in integrating variable renewable energy sources like wind and solar power. Pumped-storage hydroelectricity is the largest form of grid energy storage.

This mature, commercially available technology generates energy representing more than 99% of the installed capacity of energy storage systems [2].

The primary advantage of PHES is its high efficiency. Round-trip efficiencies of 70–80% are achievable by current PHES systems, indicating that a sizable amount of energy input is converted into electrical output. The high efficiency of PHES offers an affordable energy storage option. PHES offers a high degree of flexibility and scalability [3]. PHES systems can be designed to store large amounts of energy, making them suitable for large-scale energy storage applications. They can also react rapidly to variations in energy demand, offering useful grid balancing services. Pumped storage is an essential component of the electricity network with the ability to respond almost instantaneously to changes in the amount of electricity running through the grid.

Table 1 provides information on storage types and unit costs, between other storage (electrochemical, thermal, electrical, and hydrogen storage) and pumped storage facilities. This table is prepared with indicators by Pumped Hydro Storage International Forum (PHSIF).

According to the pumped hydro storage capabilities and costs study of this forum, pump storage investment costs are still much higher. In the most optimistic case (depending on the site characteristics) the cost would be estimated at 1 million euros/MW, but in general the estimated cost could reach 2.2 million euros/MW of installed power.

Table 1. Comparison of energy storage technologies [1, 3]

Costs	Mechanical energy storage	Electrochemical, thermal, electrical, and hydrogen storage				
	Pumped storage	Lithium-ion battery storage	Lead-acid batteries	Vanadium battery	Compressed air storage	Hydrogen
Average power CAPEX (USD/kW)	2202	3565	3558	3994	1089	3117
Average energy CAPEX (USD/kWh)	220	356	356	399	109	312
Average fixed O&M (USD/kWh/yr)	30	8.82	12.04	11.3	8.74	28.5
Effective CAPEX (USD/kW)*	2910	10570	11720	16170	3110	8890

But, compared to other PHES energy storage options, it currently has a slight advantage in terms of long-term costs. Figure 1 shows PSEH's long-term cost advantage over other sources of energy storage technologies [6].

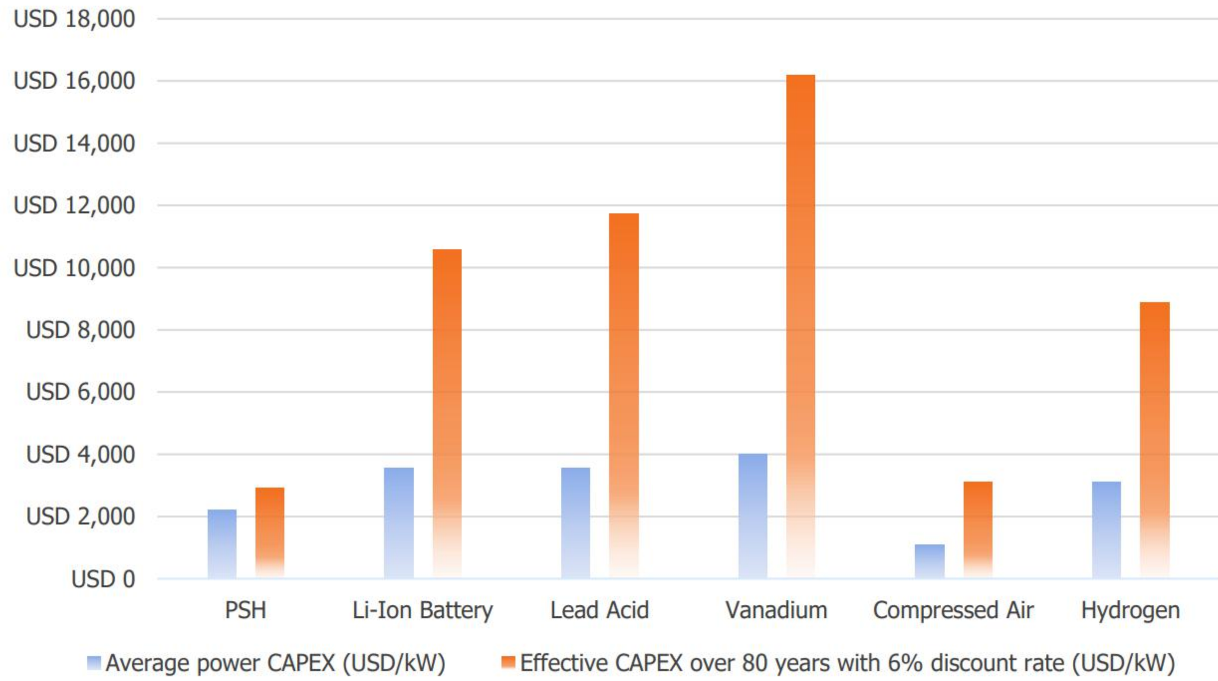


Figure 1-Comparison of effective lifetime costs of energy storage technologies over 80 years, (10-hour duration, 2020)

But, the electrochemical, thermal, electrical, and hydrogen storage can be used as a supportive vehicle to the PHES facilities, especially Lithium-ion battery technology. Lithium-ion battery technology has emerged as a dominant energy storage solution in recent years, offering several advantages that make it a valuable complement to PHES facilities. Lithium-ion batteries can support PHES and enhance energy storage systems :

1) PHES facilities, while efficient for long-term energy storage, have slower ramp-up times compared to batteries. Lithium-ion batteries can fill this gap by stabilizing the grid during sudden demand peaks or renewable energy dips, because lithium-ion batteries provide rapid response times, which are ideal for handling short-term fluctuations in energy demand and supply.

2) Lithium-ion batteries can store surplus energy during peak generation periods, while PHES handles larger, longer-duration storage. Together, they enhance the ability to smooth out renewable energy variability.

3) Combining PHES and lithium-ion batteries into a hybrid energy storage system leverages the strengths of both technologies: a) PHES offers high efficiency and capacity for long-term

energy shifts; b) Lithium-ion batteries provide quick discharge for short-term balancing and frequency regulation.

Integrating them within an energy storage ecosystem allows for a more resilient, flexible, and sustainable energy grid, capable of supporting increasing renewable energy penetration and addressing diverse energy storage needs.

According to the IHA 2022 Status Report [6], there are pumped storage power plants worldwide with an installed capacity of about 162 GW. The five countries with the highest installed capacity are listed in Table 2 [1,5].

Table 2. Top five countries with the highest installed capacities

Countries with Pumped Hydro Storage	**Installed Capacity (GW)**
China	36.0
Japan	27.5
Unite States of America	22.0
Italy	7.6
Germany	6.2

Another important component, besides the development of new units, is the refurbishment of existing units, thus benefiting from the know-how related to these rehabilitation measures, for a successful implementation of new units.

The rehabilitation of pumped hydropower plants has become a priority in the context of the energy transition and the need to integrate intermittent renewable sources into national energy systems.

In recent years, numerous modernization projects have been successfully completed, aimed at increasing the efficiency, storage capacity and lifetime of these facilities.

Table 3 presents nine such rehabilitated power plants, each exemplifying the implemented technological innovations and their contribution to ensuring the stability and flexibility of energy systems [6]. These projects are outstanding examples of global efforts to adapt to the demands of a sustainable and resilient economy.

Table 3. Upgraded Pumped Hydro Energy Storage [6]

Pumped Hydro Energy Storage	Country
Bath County	Virginia, USA
Frades II	Portugal, Europe
Goldisthal	Thuringia, Germany
Guangzhou	Guangzhou, China
Tai'An	Shandong Province, China
Shisanling	Shisanling, China
Kopswerk II	Austria
Limberg II	Austria
Ingula	South Africa

By storing excess energy generated from renewable sources, PHES offers an efficient and more environmentally friendly way to balance the grid without contributing to primary energy consumption from fossil fuels or nuclear power. Instead, it acts as a giant battery, storing excess energy during off-peak hours and releasing it during peak demand periods. Environmental benefits are reduced carbon emissions [7].

Several PHES technologies are available, including:

- Conventional PHES: are traditional open-loop systems with large reservoirs, connected to a natural water body, such as a river, lake, or reservoir, relying on the existing hydrological cycle. These systems require a continuous connection to a natural hydrological system and can be integrated into existing hydroelectric plants or reservoirs. It has lower implementation costs due to the use of existing water bodies and infrastructure.
- Closed-Loop PHES: being independent of natural bodies of water and operating with two reservoirs, built specifically for the system. These systems do not depend on hydrological characteristics or climate changes.
- Pumped Storage Hydroelectricity: Smaller-scale systems often integrated with existing hydropower plants.

Depending on the type of PHES development, the main advantages of pumped storage plants are: 1) Flexible and reliable pumped storage plants are able to react to grid fluctuations in the shortest possible time by generating the required electricity or by absorbing any excess; 2) Hybrid concepts, which combine pumped storage and wind or solar energy, represent a backup output in low wind or lack of sun; 3) "Green battery". With the current state of technology, pumped storage represents an economically viable solution to store energy on a large scale; 4) High economical value. Pumped storage plants work at an efficiency level of up to 82%; 5) Water resource management and flood control in open loop systems; 6) Exceptional lifetime of more than 80 years; 7) Symbiotic concepts. Renewable power and clean fresh water.

Although PHES offers numerous benefits, it also has drawbacks. Geographical restrictions for ideal areas, such as the presence of water sources and proper topography, may restrict the widespread use of PHES. The development of new PHES projects can be constrained by environmental concerns [8].

As far as the situation in Romania is concerned, there are pumping hydropower facilities, but they are relatively few compared to other countries. The main such facility is the Lotru-Ciunget Pumped Storage Hydropower Plant, also known as Lacul Vidra-Ciunget. It uses a water transfer system between reservoirs to produce electricity during peak periods and store energy during off-peak periods by pumping water back into the upper lake. The pumping scheme is provided for the Northern and Southern branches (put into operation in 1977-1978) of the entire Lotru development, respectively in the Petrimanu Reservoir and Pump Station (31.5 MW), the Jidoaia Reservoir and Pump Station (21 MW) and the Lotru Downstream Reservoir and Pump Station (8 MW).

Another development is represented by the hydropower project with reservoir lake from Frunzaru, on the Olt River, with an installed power of 200 MW [7], however, it is not used because it is not cost-effective and the development scheme is not complete.

Over time, there have been discussions about the realization of other pumping hydropower facilities in Romania, such as projects in the Apuseni Mountains or the expansion of existing ones, but these remained in the planning stages or feasibility studies due to financial constraints or other energy priorities [9]. According to the Commission's in-depth analysis on achieving climate neutrality by 2050, some increase in pumped storage is also anticipated—although batteries are expected to see the greatest growth [20].

2. Methodology for PHES development

2.1. Site-Specific Considerations

The study's approach involves collecting geographical, hydrological, and environmental data to identify potential PHES sites. This includes topographic maps, water resource data, and grid infrastructure maps. Data from existing hydroelectric facilities and meteorological data are also integrated into the analysis.

Site selection criteria for PHES include elevation difference, proximity to water sources, geological stability, and accessibility. Additionally, environmental and socio-economic impacts are considered to ensure the feasibility and sustainability of the project. Figure 2 shows a general layout of a PHES system [11].

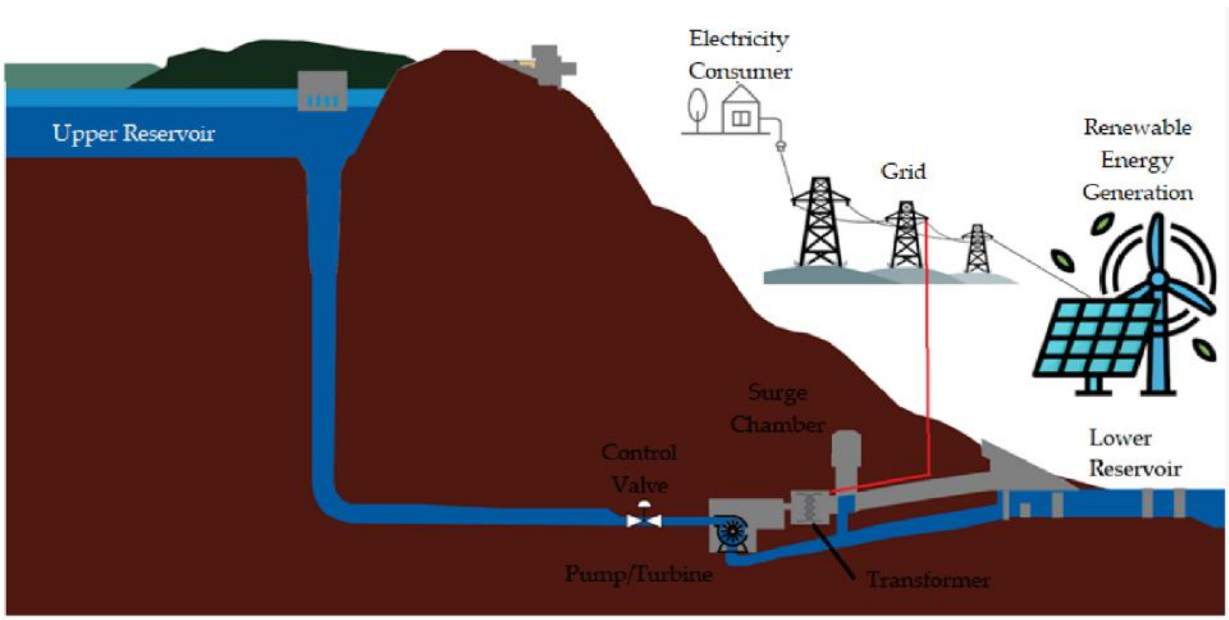


Figure 2- A possible layout of a PHES system

Several factors can limit the suitability of a site for PHES development:

- Topography: A significant elevation difference between the upper and lower reservoirs is essential to maximize energy storage capacity. Mountainous regions with steep slopes and abundant water resources are ideal for PHES [12].

- Water availability: A reliable water source is crucial to ensuring continuous operation of the PHES plant. Rivers, lakes, or artificial reservoirs can be used as water sources.

- Meteorological data: Comprehensive meteorological data is crucial for the technical, economic, and environmental feasibility of PHES projects. Limitations arising from adverse meteorological conditions can often be mitigated through innovative design and operational strategies. Early-stage feasibility studies should incorporate detailed meteorological analysis to select optimal sites and develop resilient systems.

- Data from existing hydroelectric facilities: The importance of existing data on hydroelectric power plants in the vicinity of potential PHES sites lies in its ability to influence site suitability, project feasibility, and system integration. Hydroelectric power plants and PHES facilities may compete for the same water resources. If water resources are already heavily utilized by existing plants, the availability of water for PHES operations may be constrained. Thus, detailed hydrological studies are needed to assess the balance between existing plant operations and the additional demands of PHES.

- Geological conditions: Stable geological formations are necessary to ensure the structural integrity of the reservoirs and powerhouses.

- Environmental impact: PHES projects can have significant environmental impacts, including habitat destruction, water quality degradation, and visual pollution. Careful planning and mitigation measures are necessary to minimize these impacts.

- Grid connectivity: The PHES plant should be located near a strong transmission grid to facilitate the transfer of electricity to consumers.

- Social and economic impact: The project should consider the social and economic impacts on local communities, such as job creation, land use changes, and potential displacement.

2.2. Technical analysis

The analysis involves evaluating the technical feasibility of potential sites, including geological surveys, hydrological studies, and preliminary design assessments. This analysis helps in identifying the most suitable locations for PHES development in Romania.

PHES systems can be broadly categorized into conventional (using surface reservoirs, open or closed loop) and underground (using abandoned mines or underground caverns) setups. Romania's potential lies in both types, depending on site-specific conditions. Advances in turbine and pump technology have improved efficiency and performance, making PHES a more attractive option for energy storage.

PHES systems typically have high round-trip efficiencies, ranging from 70% to 80%. Factors affecting efficiency include:

- Pump and turbine efficiency
- Head loss in the penstock and tunnels

A detailed engineering analysis would assess the technical feasibility of each site, involving the following:

- Reservoir design and construction
- Pump and turbine selection
- Powerhouse design
- Transmission line infrastructure

The analysis from a technical point of view requires the calculation and detailing of: 1) location identification, hydrological calculations regarding the availability of the water resource; 2) determining the potential energy to be stored; 3) Power required for pumping; 4) The time required for pumping; 5) dimensioning of tanks; 6) The power obtained through turbine (release of water).

1) Hydrological calculations

The first stage (in open loop systems) consists in performing the hydrological calculations in the analyzed section, regarding the available water resource, using the duration curves of the average daily and average monthly flows. Based on the results of these analyses, the available water stock is established.

2) Energy calculations

a. Potential energy to be stored:

The stored energy is determined with the following relationship:

$$E = \rho \cdot g \cdot Q \cdot H \cdot \eta \cdot t$$

where:

- E (kWh), represents the average stored energy
- ρ, is the water density (1000 kg/m³)
- g, is the acceleration due to gravity (9.81 m/s²)
- Q, is the usable discharge (m³/s)
- H, is the net head (m); the hydraulic difference between the two reservoirs
- η, represents the total efficiency of the "plant pumping" system.
- t, is the operating time (about 8 hours)

b. Power required for pumping

The power for pumping is determined with the following relationship:

$$P = \frac{\rho \cdot g \cdot Q \cdot H}{\eta_p}$$

Where:

- P (kW), represents the pumping power
- ρ, is the water density (1000 kg/m³)
- g, is the acceleration due to gravity (9.81 m/s²)
- Q, is the usable discharge (m³/s)
- H, is the net head (m); the hydraulic difference between the two tanks
- η_p, represents the pumping efficiency of the hydro unit

c. Time required for pumping

The time required to fill the tank is determined with the following relationship:

$$t = \frac{Vmax}{Q}$$

Where:

- t, pumping time (hours)
- Q, is the pump flow rate (m³/s)
- $Vmax$, is the total volume of water pumped (the volume of the upper reservoir, m³)

d. Dimensioning of reservoirs

The upper tank must have a sufficient volume to store the amount of water related to the maximum energy.

$$Vmax = \frac{Emax}{\rho \cdot g \cdot H \cdot \eta}$$

e. The power obtained by discharge

The power generated by discharge is calculated with the relation:

$$P = \rho \cdot g \cdot Q \cdot H \cdot \eta_u$$

Where:

- P (kW), represents the power of the turbine
- ρ, is the water density (1000 kg/m³)
- g, is the acceleration due to gravity (9.81 m/s²)
- Q, is the usable discharge (m³/s)
- H, is the net head (m); the hydraulic difference between the two reservoirs
- η_u, represents the efficiency of the hydro aggregate during discharge

An important technical component is the sizing and hydraulic optimization of the system, namely reduction of head losses in waterways and penstocks.

Manning's and Strickler's equations provide a foundation for calculating linear pressure losses (distributed losses) in pipes, helping engineers minimize hydraulic energy dissipation [13].

$$\lambda_M = \frac{2 \cdot g \cdot 4^{\frac{4}{3}} \cdot n_{ad}^2}{\left(\frac{D_{ad}}{m}\right)^{\frac{1}{3}} \cdot \frac{m}{s^2}}$$

where,

(D), is the pipe diameter.

(n), is the Manning roughness coefficient (or Strickler coefficient, which is the inverse of Manning's n).

(λ), is the friction factor, a dimensionless coefficient that accounts for the roughness of the channel walls and the flow conditions.

The friction factor (λ) is a crucial parameter in determining the magnitude of linear load losses. It depends on the roughness of the channel surface and the Reynolds number (a dimensionless quantity that characterizes the flow regime).

2.3. Environmental impact analysis

Adhering to sustainability standards is crucial for PHES projects. This includes minimizing environmental impact related to both location and technology, promoting renewable energy use, and ensuring long-term operational sustainability. Compliance with national and international environmental regulations is mandatory. The environmental impact of a national energy system is largely determined by its energy mix, with fossil fuels contributing significantly to emissions. Since renewable energy sources like wind and solar are intermittent and difficult to predict, the widespread adoption of electrical energy storage systems is important for mitigating their environmental impact and promoting a sustainable energy future.

PHES contributes to climate resilience by enabling greater penetration of renewable energy, reducing greenhouse gas emissions, and providing a reliable backup during extreme weather events. Its role in enhancing grid stability makes it a key component of climate adaptation strategies.

PHES projects must comply with stringent environmental regulations to protect natural habitats and water resources. This involves obtaining necessary permits, conducting environmental impact assessments, and implementing mitigation measures to minimize ecological disruption.

The ecological impact of PHES projects is a critical consideration. Developing new reservoirs or expanding existing ones can disrupt local ecosystems, affect water quality, and alter habitats. It is essential to conduct thorough environmental impact assessments (EIAs) to mitigate negative effects on biodiversity and ensure sustainable development practices.

Pumped hydro energy storage systems are essential for balancing intermittent renewable energy sources and ensuring grid stability. However, their development is often associated with significant environmental implications. In Romania, a country with diverse ecological landscapes and water systems, the deployment of PHES facilities presents both opportunities and challenges.

This chapter provides an in-depth analysis of the potential environmental impacts of PHES in Romania. It also explores mitigation measures that aim to balance the country's energy transition goals with environmental and social considerations [14].

2.3.1. Hydrological Impacts

Hydrological changes are among the most pronounced environmental consequences of open-loop PHES projects. These impacts arise due to the large-scale manipulation of water resources, which can fundamentally alter natural hydrological cycles.

The construction of reservoirs and the operation of water transfer systems disrupt natural river dynamics in several ways. Reservoirs created for PHES can impede the natural flow of rivers, affecting downstream ecosystems that depend on steady flow regimes. The presence of reservoirs also alters the sediment transport process. When water flow slows down in the reservoir, sediment tends to accumulate upstream. This accumulation can lead to sediment starvation downstream, causing increased erosion and destabilization of riverbanks.

The frequent cycling of water in PHES systems creates flow fluctuations that can significantly stress aquatic ecosystems. Organisms that rely on stable conditions, such as certain fish and amphibian species, are particularly vulnerable to these changes. In Romania, where many rivers host endemic and migratory species, such disruptions could have far-reaching ecological consequences.

The interaction between PHES reservoirs and groundwater systems can lead to unintended hydrological consequences. Seepage from reservoirs may raise local groundwater levels, which could inundate nearby lands or increase salinity in soils. Conversely, prolonged drawdown of reservoirs during peak electricity demand periods can lower groundwater tables in surrounding areas. Such changes can compromise water availability for agricultural activities and household use, particularly in regions of Romania where groundwater serves as a primary resource.

Another concern is the potential for pollutants from the reservoirs to seep into aquifers, contaminating drinking water sources. This risk is heightened in cases where the reservoir is located in regions with high agricultural activity, as nutrient runoff and pesticides could accumulate in the water[15].

2.3.2. Biodiversity and Ecosystem Impacts

The impact of PHES systems on biodiversity and ecosystems is multifaceted. These projects can lead to habitat loss, ecosystem fragmentation, and changes in species composition.

The construction of reservoirs and related infrastructure often results in the destruction or modification of habitats. In Romania, where many river systems pass through ecologically sensitive areas, this is a significant concern. Aquatic habitats are often the first to be affected. The alteration of riverbeds, changes in water flow, and fluctuations in water levels can disrupt the life cycles of fish, amphibians, and other aquatic organisms.

Terrestrial habitats are also impacted. Forested areas and grasslands may be cleared to make way for reservoirs, access roads, and power stations. This loss of vegetation can displace wildlife, reduce biodiversity, and increase the vulnerability of ecosystems to invasive species. In some cases, the fragmentation of habitats can isolate populations of certain species, reducing genetic diversity and their ability to adapt to environmental changes.

Romania is home to several protected areas, including Natura 2000 sites and national parks. Many potential sites for PHES development overlap with these protected zones. This overlap presents a challenge for developers and policymakers, as any activity in these areas is subject to strict environmental regulations.

The establishment of reservoirs in or near protected areas can have profound ecological impacts. Wetlands, which often serve as biodiversity hotspots, are particularly vulnerable. Reservoir construction can lead to the submergence of these ecosystems, resulting in the loss of critical habitats for birds, fish, and amphibians. The long-term recovery of such ecosystems is uncertain, as they are highly sensitive to changes in hydrology and land use [16].

2.3.3. Climate Change Implications

Pumped hydro energy storage (PHES) systems are often viewed as a solution to climate change because they enable the integration of renewable energy sources. However, their construction and operation have climate-related implications that merit detailed analysis.

Although PHES systems generate clean energy during operation, their construction involves significant greenhouse gas emissions. The production of materials such as concrete and steel for dams, tunnels, and reservoirs is highly energy-intensive and relies heavily on fossil fuels.

Deforestation during site preparation also contributes to emissions, as it releases stored carbon into the atmosphere and reduces the area's carbon sequestration capacity.

The land-use changes associated with PHES projects can have long-term effects on regional carbon budgets. Reservoirs often inundate areas that would otherwise serve as carbon sinks, such as forests and grasslands. The decomposition of organic matter submerged in reservoirs produces methane, a potent greenhouse gas.

Despite these challenges, PHES systems contribute positively to climate mitigation. By facilitating the integration of renewable energy sources like wind and solar, PHES reduces reliance on fossil fuels. This helps lower overall greenhouse gas emissions from the energy sector. Reservoirs can also provide ancillary benefits, such as flood control, which is increasingly important as extreme weather events become more frequent due to climate change.

However, climate change itself may impact the long-term viability of PHES by altering regional hydrology and water availability. Changes in precipitation patterns, increasing evaporation rates due to higher temperatures, and prolonged droughts could reduce the reliability of water sources required for PHES operation. In some regions, reduced water availability may limit the feasibility of new projects or necessitate modifications to existing facilities. Additionally, competing demands for water—such as for agriculture, drinking water supply, and ecosystem conservation—must be considered in future planning to ensure that PHES does not exacerbate water scarcity issues [17].

2.3.4. Social and Cultural Impacts

The social and cultural impacts of PHES projects are as significant as their environmental effects. These projects often require large areas of land, leading to displacement and disruption of local communities [18].

One of the most direct social impacts of PHES projects is the displacement of communities living in the areas designated for reservoirs or infrastructure. In Romania, many potential sites for PHES development are located in rural areas where people depend on the land for their livelihoods. Displacement can disrupt traditional agricultural practices, leading to economic and social challenges for affected communities.

In addition to the loss of homes and livelihoods, displacement often involves the loss of cultural heritage. Many rural areas in Romania are rich in archaeological sites, historical landmarks, and cultural traditions. The submergence of these sites under reservoirs results in an irreplaceable loss of cultural identity for local communities.

Public perception plays a crucial role in the success of PHES projects. In Romania, past infrastructure projects that failed to adequately address environmental and social concerns have created a climate of distrust. Communities often express concerns about the transparency of the planning process and the adequacy of impact assessments.

Effective stakeholder engagement is essential for building public support. This involves not only informing communities about the benefits and risks of PHES but also actively involving them in decision-making processes. Transparent communication and fair compensation for affected communities are critical for fostering trust and acceptance.

2.3.5. Mitigation Strategies

Addressing the environmental and social impacts of PHES requires a multifaceted approach. Comprehensive planning and the adoption of best practices can help minimize negative effects while maximizing the benefits of these systems [18].

A critical component of mitigation is Site selection. The smart site selection ensures that PHES systems deliver maximum benefits with minimal environmental and social costs. By prioritizing existing infrastructure, preserving ecosystems, and optimizing resource use, developers can enhance the sustainability of PHES projects, making them a more attractive solution for supporting renewable energy integration.

Another key strategy is ecosystem restoration. This involves rehabilitating habitats that are disrupted by PHES construction and operation. For instance, wetlands and forests near reservoirs can be restored to provide alternative habitats for displaced species. Sustainable water management practices can also reduce hydrological impacts. Designing reservoirs to maintain natural flow patterns and implementing measures to prevent sediment buildup can protect downstream ecosystems.

Community involvement is another important component. Engaging local populations in the planning process ensures that their concerns are addressed and that they benefit from the project.

Providing fair compensation, investing in community development programs, and preserving cultural heritage sites can help offset the social impacts of displacement.

Finally, adopting climate-smart design principles can reduce the carbon footprint of PHES projects. Using low-carbon construction materials, integrating renewable energy into construction processes, and optimizing reservoir operations to minimize methane emissions are some of the measures that can be implemented.

2.4. Cost-Benefit analysis

A comprehensive cost-benefit analysis considers the initial investment, operational and maintenance costs, and potential revenue from energy storage and supply. It also evaluates the economic benefits of job creation, local infrastructure development, and energy security enhancement.

Cost-benefit analysis (CBA) is a critical tool for evaluating the economic viability and overall impact of infrastructure projects. In the context of pumped hydro energy storage in Romania, this analysis considers a range of factors, including initial investment costs, long-term operational expenses, environmental and social costs, and the benefits derived from energy storage, grid stability, and renewable energy integration. This chapter delves into these aspects to provide a comprehensive assessment of the financial and societal implications of PHES development in Romania.

2.4.1. Capital Costs

The construction of PHES systems requires significant capital investment. These costs are primarily associated with the excavation and construction of reservoirs, tunnels, and underground chambers, as well as the installation of turbines, generators, and auxiliary systems [18].

In Romania, the geographical and geological characteristics of potential PHES sites can influence these costs. Sites located in mountainous regions, such as the Carpathians, may offer natural elevation advantages that reduce excavation needs. However, these same sites may require additional investment in access roads and transportation infrastructure. Costs also vary depending on the scale of the project, with larger installations benefiting from economies of scale but necessitating higher upfront expenditures.

Inflation, material prices, and labor availability also play significant roles in determining the capital cost of PHES projects. The global rise in construction material prices, including steel and concrete, has a direct impact on the feasibility of large-scale energy storage projects. In addition, the availability of skilled labor for highly specialized tasks, such as turbine installation and hydraulic engineering, can influence project timelines and costs.

2.4.2. Operational and Maintenance Costs

Operational costs of PHES systems include energy costs for pumping water during periods of low electricity demand, maintenance of mechanical and electrical systems, and environmental management practices. Although these systems are generally considered low-maintenance compared to other energy technologies [10,11] (around **50–75% lower** than thermal plants and **20–50% lower** than battery storage systems), regular inspections, repairs, and upgrades are necessary to ensure efficient performance over their decades-long operational lifespan (maintenance costs for PHES systems typically range from 1–2% of the capital cost annually, [10]).

The energy required for pumping water represents a significant recurring expense. In Romania, where electricity prices vary seasonally and regionally, this cost can fluctuate, impacting the economic return of the PHES facility. However, the ability to purchase electricity during off-peak periods, when prices are lower, can mitigate this expense.

Maintenance costs include regular servicing of turbines, generators, and control systems. Infrastructure exposed to water, such as reservoirs and pipelines, may also require periodic repairs to address wear and tear or sediment buildup. Advanced technologies, such as automated monitoring and predictive maintenance systems, can help optimize these processes and reduce costs over time.

2.4.3. Environmental and Social Costs

While the environmental and social impacts of PHES projects are detailed in the previous chapter, it is essential to quantify these impacts in monetary terms for a thorough cost-benefit analysis. Environmental costs include the loss of biodiversity, the impact on natural habitats, and greenhouse gas emissions especially during and post construction. Social costs encompass the displacement of communities, loss of livelihoods, and potential conflicts over water usage.

In Romania, the financial valuation of environmental costs often involves calculating the opportunity cost of lost ecosystem services. For instance, forests and wetlands submerged by reservoirs no longer provide benefits such as carbon sequestration, water filtration, or habitat provision. Social costs are often assessed through the compensation packages offered to displaced individuals and the investment required to rebuild infrastructure and provide alternative livelihoods for affected communities.

It is also important to consider the long-term costs of mitigating environmental damage. Restoration projects, monitoring programs, and the implementation of sustainable management practices represent additional financial commitments. Although these costs can be significant, they are essential for minimizing the long-term ecological footprint of PHES projects.

2.4.4. Economic and Energy Benefits

The primary economic benefit of PHES systems lies in their ability to store energy efficiently and provide it when demand peaks. This capability enhances grid stability, reduces the need for fossil fuel-based peaking plants, and facilitates the integration of renewable energy sources.

In Romania, the energy market is characterized by fluctuating demand and increasing penetration of wind and solar power. PHES systems can capitalize on this variability by purchasing electricity during periods of excess supply, typically at lower prices, and selling it during periods of high demand when prices are higher. This arbitrage mechanism generates significant revenue for PHES operators.

Additionally, PHES contributes to grid stability by providing ancillary services such as frequency regulation, voltage support, and spinning reserves. These services are critical for maintaining the reliability of the grid, particularly as renewable energy sources with variable output become more prevalent. The economic value of these services is often underestimated but represents a substantial benefit in markets like Romania, where energy security is a growing concern.

PHES projects also stimulate local and national economies through job creation and infrastructure development. Construction phases provide employment opportunities for engineers, laborers, and contractors, while long-term operation supports skilled positions in energy management and maintenance. Indirect economic benefits include increased demand for local goods and services, improved transportation networks, and enhanced energy security [19].

2.4.5. Cost-Benefit Comparison

A comprehensive cost-benefit analysis requires balancing the high initial and operational costs of PHES projects against their long-term economic, environmental, and social benefits. In Romania, this analysis must consider the unique characteristics of the energy market, geographical conditions, and regulatory environment.

Capital costs for PHES projects are substantial but are offset by their long operational lifespans and low variable costs. When properly maintained, these systems can operate for several decades with minimal efficiency losses. The ability to generate revenue through energy arbitrage and ancillary services further enhances their financial viability.

Environmental and social costs, while significant, can be mitigated through careful planning and adherence to best practices. The long-term benefits of reduced greenhouse gas emissions, enhanced grid stability, and improved energy security often outweigh these costs. However, these benefits are contingent on the effective integration of PHES systems into the broader energy strategy of Romania.

3. Romania's Potential of PHES development: Case studies

Pumped Hydro Energy Storage requires favorable geographical conditions, such as terrain with large elevation differences, a large land area for water storage, and a reliable water source to offset system losses due to infiltration and evaporation.

Romania has significant untapped potential for PHES [4], owing to its diverse topography and existing hydro infrastructure. The Carpathian Mountains offer numerous suitable sites for constructing reservoirs at different elevations. Additionally, Romania's commitment to increasing its share of renewable energy creates an ideal environment for integrating PHES into its energy system.

Romania possesses significant topographical features, including mountainous regions and valleys, which are ideal for PHES development. The country's abundant water resources, coupled with its growing renewable energy sector, make PHES a promising option for energy storage.

Potential sites for PHES plants include areas with significant elevation differences, such as the Carpathian Mountains and the Transylvanian Plateau.

The analysis of the potential of these types of hydropower developments in Romania was made taking into account both the already existing national data, information and studies (in different stages) and the potential sites highlighted by international analyzes such as the Global Atlas [4].

Taking into account the available data and information from the national level, 4 case studies are presented, namely Tarnita-Lapustesti, Colibita, Socol and Frasin-Pangarati.
Regarding the potential highlighted by the Global Atlas [4], the following development scenarios were analyzed:

1) creation of two new reservoirs;
2) the creation of a single reservoir, thus using the existing hydrotechnical infrastructure (sources: the Danube River and the existing reservoirs within the hydrotechnical schemes);
3) Create PHES reservoirs on flat ground, for more siting options;
4) Repurpose mining sites for pumped hydro reservoirs.

Regarding Solution 1), namely the creation of two reservoirs, it is considered impractical from both a cost perspective and an environmental standpoint. The investment becomes unprofitable with the additional costs of a reservoir compared to the proposed solutions, which involve a storage lake/the Danube.

Regarding Solution 3), following the analysis of the locations, it can be easily highlighted that, in general, they involve overlapping with localities, which would require the relocation of the inhabitants.

Solution 4) has the major deficiency that such a facility involves extremely high costs in mine safety works. Moreover, it is difficult to seal a mine, so water infiltration will lead to the contamination of groundwater, causing significant changes in its chemistry and level.

Of these, only Solution 2) is feasible and only under the conditions in which the dykes closing the reservoir are less than approx. 60 m high. Under today's conditions in Romania, the construction of dams higher than 20 meters is unsuitable both in terms of investment costs and environmental issues. Although small dams are considered to have a lower environmental impact due to the reservoir volume, measures to reduce their environmental impact must be integrated early on to be taken into account when designing the works and conducting economic studies [21].

Thus, the best identified options are presented in the following centralized table. **It should be highlighted that the entire analysis assumes the identification of optimal sites that are not located in any type of nature protected areas .**

Table 4. Optimal potential sites [23]

Location/	**Dam Wall Hight [m]**
Colibita	5
Socol	16
Frasin-Pangarati	30
Tarnița –Lăpuștești	33
Simian	33.9
Oasa Lake - Cugir	54.6
Poiana Marului Lake	55.7
Oasa Lake - Girbova	58.2
Oasa Lake - Plesi	60.4
Siriu Lake	60.9

From the point of view of energy indicators, these case studies are detailed below.

3.1. Tarnița –Lăpuștești case study

The proposed site is located in Cluj County, approximately 30 kilometers upstream from Cluj-Napoca municipality, along the Someșul Cald River Valley, on the left bank to the existing Tarnița Reservoir [9] .

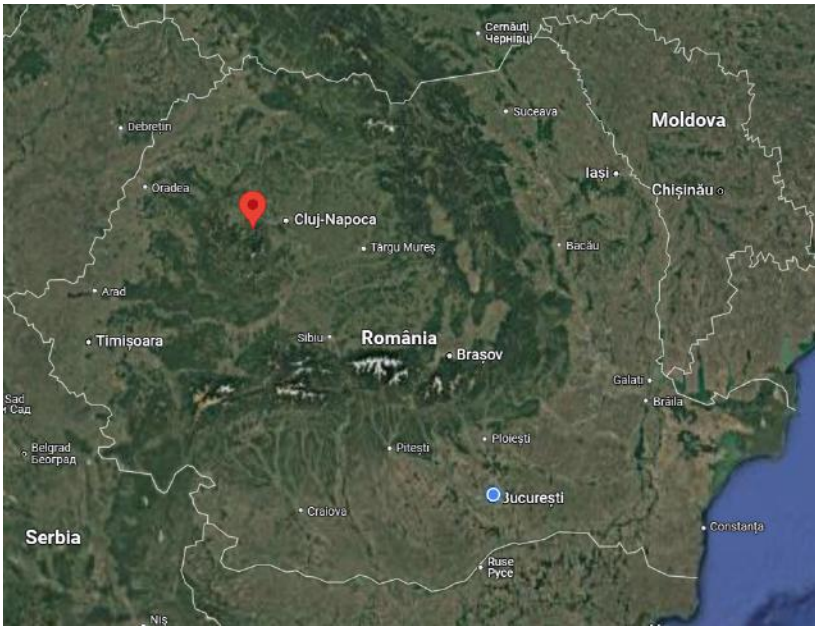


Figure 3- The Tarnița–Lăpuștești location (46°43'15.3"N 23°13'01.6"E)

The Tarnița-Lăpuștești pumped-storage hydropower plant project is studied here to assess the advantages and disadvantages that such a plant offers to the National Energy System (NES).

Advantages:

- Increasing the security of the NES within the UCTE framework;
- Transferring electrical energy from low-load periods to peak consumption times;
- Arbitrage in the electricity market through optimized consumption and production;
- Providing short-term emergency reserves;
- Supplying secondary and tertiary reserves required to balance the NES;
- Frequency-power regulation and maintaining spinning reserve;
- Providing reactive reserves and voltage regulation within the NES;
- Facilitating energy exchange through UCTE interconnections;
- Black start capability, essential for restoring the network in the event of a total power outage;
- Integrating and managing intermittent renewable energy sources, creating optimal conditions for installing over 4,000 MW in wind power plants;
- Reducing natural gas consumption by replacing 2,000 MW of gas turbines with 1,000 MW in pumped-storage hydropower plants (PHES) [9];

- Reducing greenhouse gas emissions by avoiding the use of gas turbines. Without the Tarnița-Lăpuștești PHES project, this functionality would be assumed by gas plants, generating annual emissions of approximately 682,000 tons of CO_2, totaling 34.10 million tons of CO_2 over 50 years.

Disadvantages:

- Despite being a relatively low-emission energy storage solution, the Tarnița-Lăpuștești PHES involves significant land and water use. The creation of reservoirs, especially the upper reservoir, could impact local ecosystems, biodiversity, and water flow. The alteration of natural habitats may lead to long-term ecological changes.
- The construction of PHES systems, including the Tarnița-Lăpuștești project, requires substantial upfront investment. The costs associated with building dams, reservoirs, underground galleries, turbines, and other infrastructure can be quite high. Although operational costs are relatively low, the initial capital can pose a significant financial burden.
- Obtaining the necessary permits and environmental clearances for PHES projects can be time-consuming and politically challenging. In Romania, the construction of the upper reservoir and related infrastructure may face opposition from local communities, environmental groups, and regulatory bodies, especially if the project impacts protected areas or land use. It is possible that even a part of local residents in Cluj opposes and could mobilize strongly, including challenging the regulatory acts in court, further slowing the construction process or even stopping it, making this site an even more problematic one.
- The construction of new reservoirs and related infrastructure can create conflicts with landowners, local populations, and other stakeholders. In the case of the Tarnița-Lăpuștești PHES, potential land acquisition and changes in land use patterns could lead to disputes or opposition from affected communities.
- As with any large infrastructure project, there are risks associated with the geology of the site. Changes in water levels, landslides, or the failure of dams and reservoirs are rare but catastrophic risks.
- The efficiency of the PHES is largely dependent on the availability of water resources and the hydrological conditions of the area. In periods of drought or lower-than-expected rainfall,

water storage and power generation could be compromised, which would affect the plant's ability to meet peak demand.

- While PHES systems are valuable for balancing grid demand, they are not as flexible as other storage solutions, such as batteries, in terms of rapid response times or capacity scaling. The Tarnița-Lăpuștești PHES, like other hydroelectric systems, has a set operational cycle and cannot respond as quickly to sudden changes in grid frequency or demand fluctuations.

The Tarnița-Lăpuștești PHES would have an installed capacity of 1,000 MW, distributed across 4 reversible motor-generator groups, each with a capacity of 250 MW. The plant would produce 1,625 GWh of electricity annually and consume, in pumping mode, 2,132 GWh/year, with a transformation coefficient of 0.76, comparable to the most modern operating pumped-storage plants globally [9].

The primary layout includes an upper reservoir—Lăpuștești Lake, which would be constructed—and an existing lower reservoir—Tarnița Lake. Tarnița Lake has a total volume of 74 million cubic meters, of which 15 million cubic meters are available for the pumped-storage plant, between a minimum operating level of 514 meters above sea level and a normal retention level of 521 meters above sea level.

The advantages of the site include:

- The existence of the lower reservoir—Tarnița accumulation with NNR = 521.50 meters above sea level and NmE = 514.00 meters above sea level, reducing investment costs by approximately 30%.

- The presence of the Lăpuștești plateau at an average elevation of 1,070 meters on the left bank of the Someșul Cald River, adjacent to the existing Tarnița accumulation, suitable for the construction of the upper reservoir (Lăpuștești accumulation).

- The potential to achieve an average gross head of 564.5 meters between the upper and lower reservoirs, which allows for a reduction in the volume of the upper reservoir.

The existing Tarnița accumulation is part of a cascade of 8 hydropower plants, 5 dams, and 30 kilometers of main and secondary conduits developed along the Someș River.

The Tarnița-Lăpuștești PHES project consists of the following main components:

1. Upper Reservoir (Lăpuștești accumulation) with a volume of 10 million cubic meters, located on the Lăpuștești plateau (1086.00 meters above sea level), constructed through excavation and embankments to balance the volume of excavations and fillings.

2. Lower Reservoir (Tarnița accumulation) with a useful volume of 15 million cubic meters out of a total of 70 million cubic meters, located on the Someșul Cald River at a valley floor elevation of 441.00 meters above sea level. It is formed by the Tarnița concrete arch dam (521.50 meters above sea level and a minimum operating level at 514.00 meters above sea level).

3. Hydraulic Conveyances, including:

o High-pressure tunnels (two lines) connecting the upper reservoir to the powerhouse, with a length of 1,096 meters and a diameter of 4.30 meters.

o Low-pressure tunnels (two lines) for water discharge and suction, with a length of 1,325 meters and a diameter of 6.20 meters.

4. Powerhouse, an underground structure located on the left bank of the Tarnița accumulation, comprising machine and transformer caverns, access tunnels, connection galleries, suction galleries, valve shafts, and cable galleries.

The powerhouse would be equipped with four binary turbine-pump units coupled with generator-motor systems, each with an installed capacity of 250 MW.

Table 5. Technical Characteristics of the Turbine-Pump

Type		Reversible Francis with vertical shaft
Number of turbine-pump units		4
Net head in turbine mode	Maximum/nominal/minimum	570 m/540 m/520 m
Maximum flow in turbine mode		53 mc/s
Maximum power with coupling		260 MW
Pumping head	Maximum/nominal/minimum	580 m/560 m/540 m

Maximum flow in pump mode	38 mc/s
Maximum absorbed power	258 MW
Rotor characteristic diameter	3800 mm
Nominal speed	600 rpm
Back pressure	70 m

In the end, the Tarnița-Lăpuștești PHES project would have the following hydro-energy and construction parameters, presented in Table 6.

Table 6. Final technical characteristics

Parameter	U.M.	Value
• NNR upper reservoir (Lăpuşteşti reservoir)	maSL	1086
• Minimum upper reservoir level (Lăpuşteşti reservoir)	maSL	1053.5
• NNR lower reservoir (Tarniţa reservoir)	maSL	521.5
• Center of gravity level (Tarniţa reservoir)	maSL	518
• Minimum level of energy exploitation (Tarniţa reservoir)	maSL	514
• Upper tank volume (Lăpuşteşti reservoir)	mil. m^3	10
• Maximum gross head (1086-514)	m	572
• Average gross head (1086-521.50)	m	564.5
• Minimum gross head (1053,50-521,50)	m	532
• Maximum flow at turbine	m^3/s	4 x 53
• Maximum pumping flow rate	m^3/s	4 x 38
• Equipment: 4 reversible turbine pump groups: - in generator mode - in engine mode	 MVA MW	 4 x 280 4 x 250
• Installed power	MW	1.000
• Pumping cycle	weekly	
• Energy produced in generator mode	GWh/an	1.649
• Energy consumed in pump mode	GWh/an	2.103
• Transformation coefficient	0,78	
• Secondary adjustment f/P	MWh	916.300
• Fast tertiary reserve	MWh	4.108.650
• Dispatchable consumption system service	MWh	2.352.000

Taking into account the load curve of PHES Tarniţa–Lăpuşteşti, the simulation of the operation plan of a typical average week (which characterizes a multiannual average year) was carried out, with the following mode of operation [9]:

The total number of pumping/turbinating hours per week is [9]:

- number of pumping hours: total number of pumping hours/week: 72 h.
- number of turbine hours:
- total number of turbine hours / week: 48 h.

Taking into account this information and the fact that the upper tank must go through a complete filling-emptying cycle during a week, the consumed and produced energies were determined [9]:

- pumped energy / week 42.93 GWh; total pumped energy / year 2,103.33 GWh;
- energy produced / week 33.66 GWh; total energy produced / year 1,649.46 GWh.

Conclusion

Regarding the characteristics of the site, it presents obvious advantages (head, installed flow, diameter of the penstock, power and energy obtained, etc.). But, a great uncertainty in the return on investment is the volatility of the current electricity price and the risk of construction being halted due to civil courts. Also, an installed capacity of 1000 MW would put significant pressure on the energy grid. Thus, it is recommended to limit the installed power to a maximum of 300 MW. From an environmental point of view, while there isn't a detailed environmental study, the project would heavily disrupt the nearby habitats and longitudinal connectivity of the river. The construction of the upper reservoir and associated infrastructure would lead to deforestation, soil erosion, and the displacement of wildlife. Additionally, alterations to water flow patterns could impact aquatic ecosystems, affecting fish populations and other species reliant on stable hydrological conditions. The reservoir could also contribute to greenhouse gas emissions due to the decomposition of organic material in flooded areas, albeit at a much lower level compared to fossil fuel alternatives. Furthermore, the project's impact on water quality must be considered, as fluctuations in reservoir levels and sediment transport could lead to increased turbidity and potential nutrient imbalances. The risk of habitat fragmentation is another concern, as the presence of new infrastructure could create barriers for terrestrial and aquatic species, disrupting migration patterns and genetic diversity. To mitigate these environmental impacts, a comprehensive Environmental Impact Assessment (EIA) should be conducted, including measures for habitat restoration, fish migration solutions, and sustainable land-use planning.

Additionally, stakeholder engagement with local communities and environmental organizations will be crucial in addressing concerns and ensuring ecological considerations are integrated into the project's development.

3.2. Colibita case study

The proposed site for the pumped-storage hydropower plant is located on the Bistrița River (cadastral code II.1.21.4), a second-order tributary of the Someș River, approximately 40 km upstream from the city of Bistrița, and around 400 m upstream from the confluence with the Repedea stream. It is situated between the localities of Bistrița Bârgăului and Mița, in Bistrița-Năsăud County in a Natura 2000 site.

The hydrological basin for the Colibița development is situated within the Călimani and Bârgău Mountains, with a drainage area of 133 km². Access to the reservoir is provided by the Bistrița-Vatra Dornei national road and the Prundu Bârgăului-Colibița county road.

Figure 4- The Colibita location (47°06'52.6"N 24°54'42.4"E)

The pumped storage hydroelectric development would be built on the Bistrița River and would include 1 facility located near the village of Colibita in the Bistrita Bargaului, Bistrita Nasaud County.

The optimal technical and economic solution for PHES Colibita is the construction of a pumped storage hydroelectric power plant in a single stage.

In order to achieve the objectives of the investment project, 3 development options were analyzed with the aim of selecting the most advantageous options:

-Option I: the solution of building a rockfill dam on a tributary of the Valea Neagra River at an elevation of 1290.00 m above sea level, dam with a height of 80 m and a crown length of 400 m.

- Option II: the solution of creating an anthropic lake with a height of 5 m at an elevation of 1560.00 m above sea level, west of Dealul Calului, with a lake surface area of 0.25 km^2. The lake would have a useful volume of 0.45 million m^3, resulting in an installed flow of 15.5 m^3/s and an installed power of 100 MW.

- Option III: the solution of creating an anthropic lake with a height of 5 m at an elevation of 1560.00 m above sea level, west of Dealul Calului, with a lake surface area of 0.40 km^2. The lake would have a useful volume of 1.5 million m^3, resulting in an installed flow of 44 m^3/s and an installed power of 260 MW.

The optimal technical and economic solution for PHES Colibita is a pumped storage hydroelectric power plant, composed of (Option III):

- the lower lake - existing; Colibita Lake, whose level variation would change by approximately 0.5 m in the event of the plant operating on a turbine - pumping cycle.

- the upper lake - to be built at an elevation of 1560.00 m above sea level, with an area of 0.4 km^2 and a circumference of approximately 4 km. The lake would not have effluent flows and would be fed through an underground gallery 5.0 km long and 5.5 m in diameter, from the lower lake. The volume of the created accumulation would be approximately 1.5 million m^3 and would ensure an installed flow of 44 m^3/s, for an 8-hour/day operation. The construction of the facility would exploit the natural fall of 762 m. Installed power 260 MW.

- the adduction would consist of an underground gallery over a length of 5 km and a diameter of 5.5 m and four penstocks over a length of 500 m.

Option 1 was avoided due to the exploitation problems of the dam, on the one hand, but also for reasons related to the necessary quantities of material.

Option 2 does not exploit the favorable local terrain conditions to the maximum. The resulting power is 100 MW, power considered insufficient under the given conditions.

The recommended variant is advantageous due to the optimal economic investment costs and the unitary technological solution. The plant is particularly useful because:

- ensures short-term emergency reserve;

- provides reactive power and operation in compensatory mode ensuring compliance with electricity quality standards;

- improves the participation of NES in the single electricity market, increasing the degree of safety and the possibility of its exploitation under superior technical and economic conditions.

The main characteristics of the pumped storage are:

- installed power 260 MW (for the calculation of the power it was considered that the level in the downstream lake would not decrease by more than 20 m compared to the normal retention level), the installed power of the pump group is 365 MW;

- 4 Francis turbines;

- 4 pumps;

- gross head 762 m;

- pumped height 762 m;

- maximum pumping efficiency 0.85, respectively turbine 0.90;

- diameter of the intake gallery 5500 mm.

The variation in time of the electrical load requires certain ways of fitting different categories of power plants into the system:

- nuclear power plants operate at the lower base of the load graph with Tu=7000-8000 h/year, where Tu=E/Pi;
- thermoelectric power plants with lignite and lower coal combustion operate at the second base, with Tu=5500-6500 h/year;
- gas-fired power plants fall at the semi-base, Tu=5000 h/year;

- river hydroelectric power plants and those with small falls H, high flows Q and very low useful volumes in lakes Vu fall at the semi-base or semi-peak, with Tu=3500-5500 h/year;
- gravity hydroelectric power plants, with lakes and large falls, operate at the peak of the load graph, with Tu=1500-2500 h/year;
- micro-hydroelectric power plants operate at the lower base, (derivative type) and are currently beneficiaries of green certificates;
- hydropower transformers (The) are useful and economical at high and short-term peaks, with Tu below 1500 h/year.

From a financial point of view, the revenue forecast is highlighted in Table 7.

Table 7. Revenue forecast (estimated for the year 2024)

System service	Minimum price Euro/MWh	Maximum price Euro/MWh	Amount Euro	Minimum income Euro	Maximum income Euro
Secondary setting*	20.55	24	45,552.00	936,093.60	1,093,248
Quick tertiary adjustment*	10.2	12	1,898,000	19,359,600	22,776,000
Dispatchable consumption*	10.2	16.5	1,138,800	11,615,760	18,790,200
Electricity production	200	250	759,200.0	151,840,000	189,800,000
Electricity consumption	100	150	1,065,800	106,580,000	159,870,000
Total income				183,751,453	232,459,448
Total expenses				106,580,000	159,870,000
General total				77,171,453	72,589,448

Note. Energy prices have changed in the last 3 years, due to the installation of photovoltaic energy sources, which make hourly prices volatile during the day, an atypical situation not studied for PEHS installations, which had differentiated day/night prices. (ANRE)

Electricity prices are the result of a synthesis of the hourly price variations in the Day-Ahead Market (DAM/PZU), with the caveat that significant variations occurred during certain periods of the year when peak energy prices were lower than base energy prices, although these were exceptions. Appendix 1 provides examples of hourly price variations for a few selected days. The development of new production capacities from renewable energy sources, particularly photovoltaic, will alter the evolution of hourly prices, resulting in atypical curves for peak energy and base energy.

Conclusion

PHES Colibița is cost-effective and has the potential for efficient connection to the National Energy System, being located between two significant points, Iernut and Stejaru. The existence of a large storage reservoir minimizes the fluctuations in pumping and utilization levels, reducing the impact on water usage in the Colibița dam section. There are also 2 significant disadvantages to this site, firstly, the entire project is located in a Natura 2000 site, already affected by the lack of ecological flow downstream of the existing HPP and the illegal construction of the micro-hydropower plant on Budușel , and secondly, tourism economic agents already developed in the area that may be dissatisfied by variations in the lake level (0.5 m). From an environmental perspective, while the project provides a renewable energy solution, it also presents significant ecological challenges. The construction of the upper reservoir and its associated infrastructure may lead to habitat destruction, deforestation, and disruption of local biodiversity. The alteration of water flow could impact aquatic ecosystems, particularly fish populations and other species dependent on stable hydrological conditions. Additionally, variations in the water level of Colibița Lake may contribute to increased sedimentation and changes in water quality, potentially affecting both the ecosystem and recreational activities. To mitigate these concerns, thorough environmental impact assessments and conservation measures should be integrated into the project's development, including habitat restoration, ecological flow maintenance, and collaboration with environmental organizations to minimize ecological damage while maximizing energy benefits

3.3. Socol case study

This is a 300 MW pumped-storage hydroelectric power plant, forming part of a much larger complex – the "Renewable Electricity Production Complex in Socol Commune, Caras-Severin County." The power plant was initially proposed for 1000 MW, but economic and environmental considerations indicate that 300 MW represents the optimal capacity.

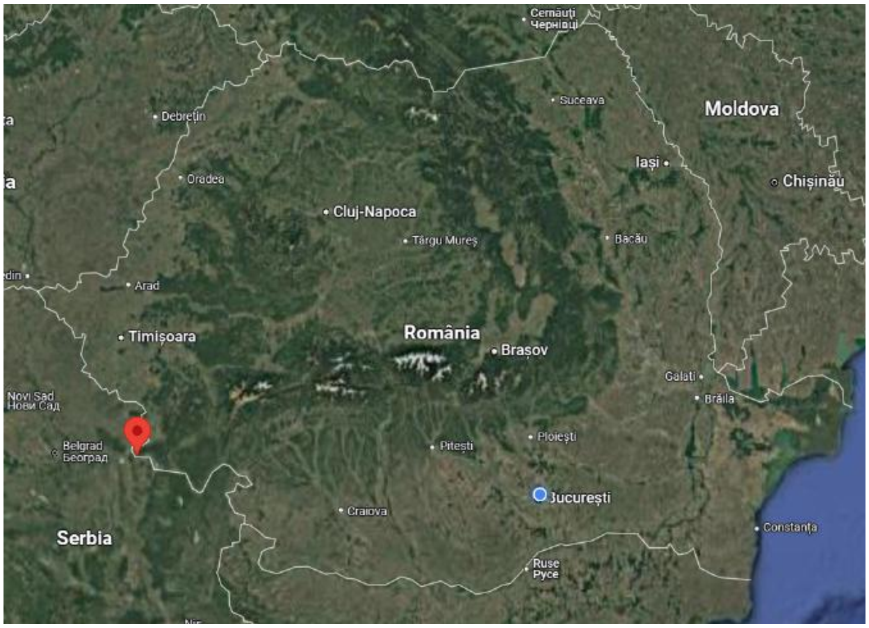


Figure 5- The Socol location (44°48'29.0"N 21°25'25.2"E)

The Socol PHES (Pumped Hydroelectric Storage) project consists of the following main components:

1. Upper Reservoir: With a volume of 3.8 million m^3, located on the plateau (NNR 305 meters above sea level). It is constructed through excavation and embankments to balance the volume of excavations and fillings.

2. Lower Reservoir: Iron Gate I (level is 80 meters above sea level).

3. Penstocks: Ten penstocks connect the upper reservoir to the power plant, with a length of 2,000 meters and a diameter of 3 meters.

4. Powerhouse: An underground structure located on the left bank of the Danube. It comprises machine and transformer caverns, access tunnels, connection galleries, suction galleries, valve shafts, and cable galleries.

The powerhouse would be equipped with five binary turbine-pump units coupled with generator-motor systems. Each unit has an installed capacity of 50/75 MW with a gross head of 220 meters.

The consumed and produced energies are:

- pumped energy: 10.6 GWh/ week

- total pumped energy: 525 GWh/ yr
- energy produced: 8.4 GWh/ week
- total energy produced: 410 GWh/ yr

The economic analysis of this project closely resembles that of the Colibița PHES project in terms of financial figures.

MOE-HPG Timișoara SRL proposes building a 1000 MW power plant at this location. However, an environmental impact assessment indicates that a plant of this size would have a significant negative environmental impact. Furthermore, the analysis suggests that a 250 MW plant would adequately meet the storage needs of the complex. This smaller plant offers several advantages: lower environmental impact, more favorable specific investment costs, resulting in improved profitability, but comes with even worse disadvantages such as: being located in the Iron Gates Natural Parc in the Danube Gorge, one of the most valuable landscape areas in Europe, already affected by the dam and the associated reservoir, and the history between Romania and Serbia regardin Iron Gates 3.

Conclusion

While a 250 MW pumped-storage plant appears to be the most viable option from an economic and operational standpoint, the significant environmental concerns at the Socol site cannot be overlooked. The project's location within the Iron Gates Natural Park—a region of exceptional ecological and cultural value—raises serious sustainability challenges. The existing environmental pressures from the Iron Gates I and II dams have already altered the natural landscape and ecosystem dynamics, and additional infrastructure development could further disrupt local biodiversity, water quality, and habitat integrity. The long-term viability of the project should not be assessed purely on economic grounds but also through the lens of environmental stewardship and regional ecological resilience.

3.4. Frasin – Pângăraţi case study

The PHES (Pumped Storage Hydroelectric Power Plant) Frasin – Pângăraţi project is planned in Neamț County, on the left bank of the Bistrița River, near the 220/110 kV Stejaru substation. It is designed to contribute to balancing the national energy system by operating in night-time pumping mode.

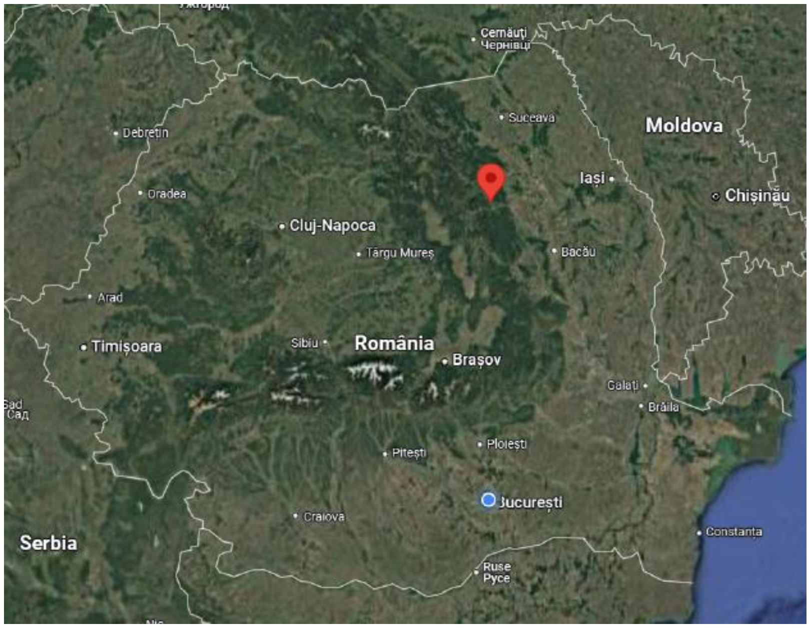


Figure 6- The Frasin – Pângăraţi location (46°58'40.9"N 26°09'09.7"E)

Main technical characteristics:

• Upper reservoir: located at an elevation of 1022 maSL, with a useful volume of approximately 3 million m³ of water.

• Gross head: approximately 500 m, between the elevation of the upper reservoir and the minimum operating level of Lake Bicaz (520 m above sea level).

• Installed power: 300 MW, limited by the current configuration of the Stejaru substation, which does not operate at 400 kV. The system is designed with two reversible groups of 157 MW each, for a total power of 314 MW.

• Construction duration: estimated at 4 years.

• Connection to the grid: it will be carried out through the 220 kV Stejaru-Gheorghieni overhead power line (OPL). A possible extension to 400 kV would increase the investment by €40 million.

Operating parameters:

• Efficiency: overall efficiency at flow: 82.8%.

overall efficiency at pumping: 76.5%.

• Operating time: flow/pumping time: 10.15 hours.

• Installed flow rate: 73.9 m^3/s.

Energy consumption and production:

• Daily energy consumed: 4736 MWh.

• Daily energy produced: 3140 MWh.

Costs and investment recovery:

• Total investment: approximately €300 million (calculated at €1 million/MW installed).

• Estimated annual revenues: €26.78 million, assuming a 95% utilization factor.

• Simple investment recovery time: 11.2 years.

Analyzed alternatives:
An identified alternative is the construction of a similar plant on the Siret River, at Călimănești, for a maximum power of 150 MW. However, the implementation of this project depends on a detailed geological study, as the clay-spongy soil of the Călimănești hill may affect the viability of the site.

Conclusion

The PHES Frasin – Pângărați project offers a robust solution to enhance the regulation capacity of the national energy grid. Strategically located outside protected areas and on the expansive Bicaz Lake, the facility will operate with minimal environmental impact, as the water level variations in the lake will be imperceptible. The project's efficient design, with a high overall efficiency of 82.8% at flow and 76.5% at pumping, ensures optimal energy production while supporting grid stability. The connection to the Stejaru substation, along with a feasible payback period of 11.2 years, further underscores the project's economic viability. However environmental considerations must be carefully integrated into the planning of this PHES.

3.5. Simian case study

The studied site is located in Simian, Mehedinti county, Romania, located in the South-West part of Romania in the Natura 2000 Opranesti site.

The analyzed pumping facility presumes a flow rate of 784 m³/s. from the Danube River and the creation of a reservoir at 283 maSL with an area of 312 ha and a volume of 100.5 GL. Delimitation of the reservoir to be done by contour dykes with a height of 33.9 m [23].

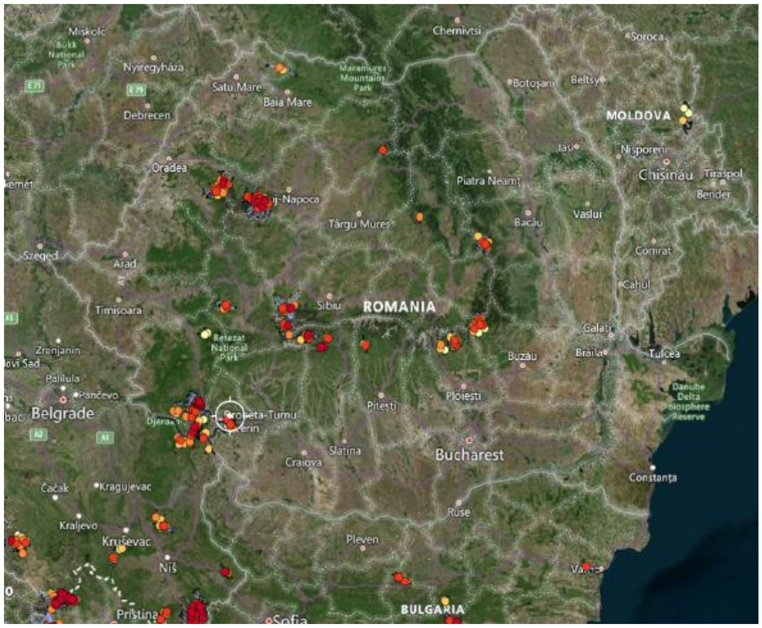


Figure 7- The Simian location (44°40'11.5"N 22°46'20.1"E)

Main technical characteristics:

• Upper reservoir: located at an elevation of 283 maSL, with a useful volume of approximately 100.5 GL of water and an area of 312 ha.

• Gross head: approximately 246 m, between the elevation of the upper reservoir and the level of Danube.

• Pipe length: 7.5 km.

• Turbine power: 1565 MW.

• Pumping power: 2471 MW.

Operating parameters:

• Efficiency: overall efficiency at flow: 82.8%.

overall efficiency at pumping: 76.5%.

• Operating time: flow/pumping time: 10 hours.

• Installed flow rate: 784 m³/s.

Energy consumption and production:

• Daily energy consumed: 24710 MWh.

• Daily energy produced: 15650 MWh.

Conclusion

The studied site in Simian, Mehedinti County, Romania, located within the Natura 2000 Opranesti site, presents a challenging but technically ambitious project. The proposed pumping facility, with a flow rate of 784 m³/s from the Danube River, a reservoir at 283 m a.s.l., and a volume of 100.5 GL, offers significant energy production potential. However, several critical factors must be considered in the long-term feasibility of this project. The flow rate is exceptionally high, and while it seems feasible in theory, in practice, it cannot be maintained consistently from the Danube due to its scale. The size of the infrastructure, particularly the water supply system, is extensive, making the implementation costs impractical. The investment required for such a large-scale system, given the constraints on the water supply, would be prohibitively expensive, especially when considering the challenges associated with the pipe length and diameter. Reducing the diameter of the pipe to manage costs would only lead to higher water velocities, which would increase energy losses exponentially, further decreasing the project's efficiency. From an environmental perspective, while this project could offer substantial energy production benefits, it is essential to consider its potential impact on the surrounding ecosystem. The location is part of the Natura 2000 network, which aims to protect Europe's most valuable and threatened species and habitats. The creation of a large reservoir, the extensive infrastructure required, and the manipulation of the Danube's flow could disrupt local wildlife habitats, alter water quality, and affect biodiversity. Additionally, the construction and maintenance of the pumping system could lead to soil erosion and deforestation, all of which could have long-lasting environmental consequences. In conclusion, while the technical specifications of the site offer some attractive possibilities, the project's feasibility is hindered by both economic and environmental concerns. The significant investment required, along with potential ecological impacts, makes the realization of this project in its current form unrealistic. Further environmental assessments and alternative designs would be necessary to ensure that such a project aligns with sustainability goals and minimizes its ecological footprint.

3.6. Poiana Marului case study

The studied site is located in the town of Caransebes, Caras-Severin county, Romania, located in the western part of Romania in a Natura 2000 site.

The pumping facility analyzed involves taking a flow of 1543 m^3/s from the Poiana Marului reservoir and creating a reservoir at an elevation of 320 maSL with an area of 374 ha and a volume of 92.8 GL. Delimitation of the reservoir to be done by contour dykes with a height of 55.7 m [23].

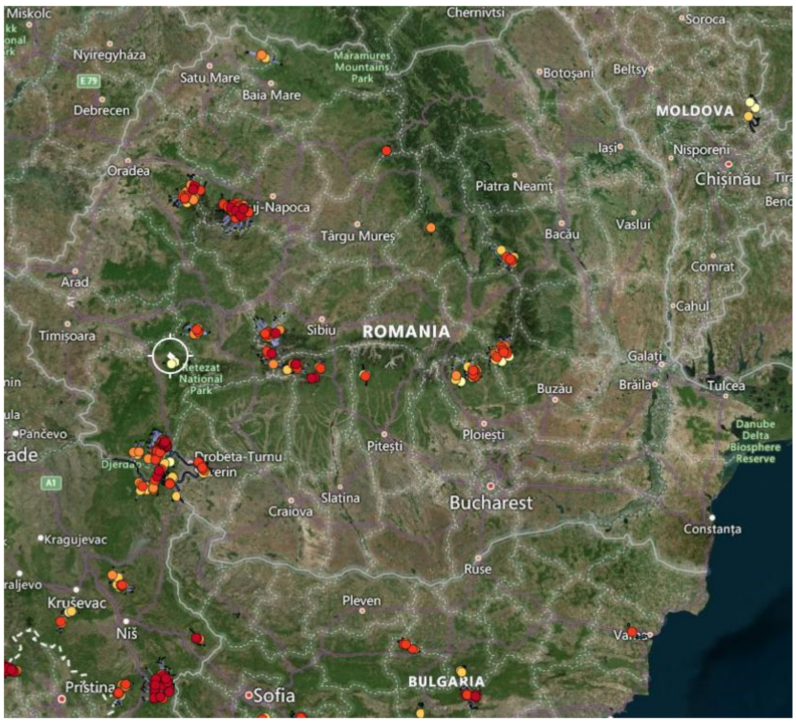


Figure 8- The Poiana Marului location (45°29'36.9"N 22°25'12.0"E)

Main technical characteristics:

• Upper reservoir: located at an elevation of 320 maSL, with a useful volume of approximately 92.8 GL of water and an area of 374 ha.

• Gross head: approximately 252 m.

• Pipe length: 6.8 km.

• Turbine power: 3158 MW.

• Pumping power: 4985 MW.

Operating parameters:

• Efficiency: overall efficiency at flow: 82.8%.

overall efficiency at pumping: 76.5%.

• Operating time: flow/pumping time: 10 hours.

• Installed flow rate: 1543 m^3/s.

Energy consumption and production:

• Daily energy consumed: 49849 MWh.

• Daily energy produced: 31575 MWh.

Conclusion

The installed flow of this project would be very high and the costs of implementing such a system for this flow make the investment unrealistic. Also important to note is that this project should not facilitate the resumption of illegal construction works on the Bistra River in Bucova, in order to ensure a larger water supply in the Poiana Mărului reservoir. From an environmental perspective, the location of the project within a Natura 2000 site adds another layer of complexity. Careful consideration of the potential impacts on local ecosystems and biodiversity is essential to ensure the project aligns with environmental protection goals. The construction of the reservoir and the associated infrastructure could have repercussions on water quality, local flora and fauna, and the natural hydrological balance.

3.7. Oasa Lake case studies

The studied location is in the vicinity of Alba Iulia, Romania, located in the central area of Romania.

Three locations are being studied for this site, namely: upper reservoir in the area of Girbova locality, Plesi locality, respectively Cugir locality.

3.7.1. Girbova case study

The pumping facility analyzed involves taking a flow of 453 m³/s from the Oasa reservoir and creating a reservoir at an elevation of 380 maSL with an area of 105 ha and a volume of 27.4 GL. Delimitation of the reservoir to be done by contour dykes with a height of 58.2 m [23].

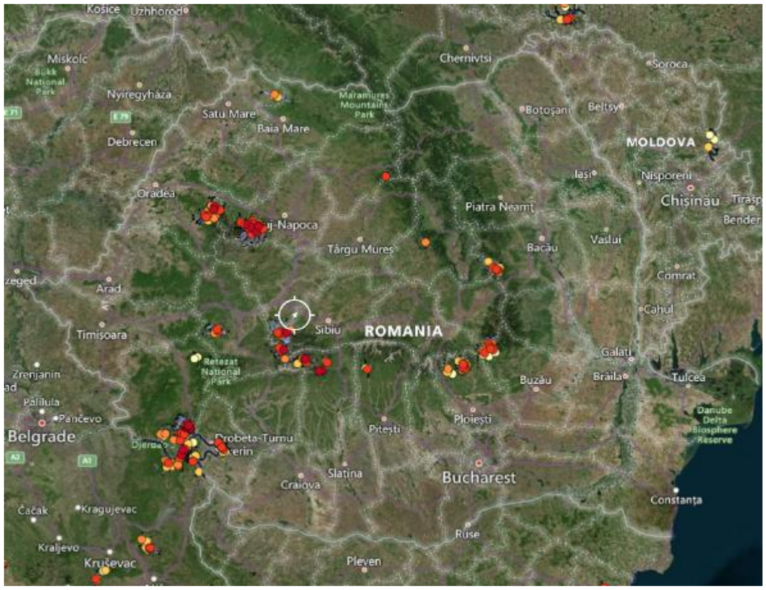


Figure 9- Oasa Lake: Girbova location (45.84411°N, 23.71742°E)

Main technical characteristics:

• Upper reservoir: located at an elevation of 380 maSL, with a useful volume of approximately 27.4 GL of water and an area of 105 ha.

• Gross head: approximately 854 m.

• Pipe length: 28.4 km.

• Turbine power: 3139 MW.

• Pumping power: 4956 MW.

Operating parameters:

• Efficiency: overall efficiency at flow: 82.8%.

overall efficiency at pumping: 76.5%.

• Operating time: flow/pumping time: 10 hours.

• Installed flow rate: 453 m³/s.

Energy consumption and production:

• Daily energy consumed: 49556 MWh.

• Daily energy produced: 31390 MWh.

Conclusion

The Girbova case study presents a high-flow pumping facility designed to take a substantial 453 m^3/s from the Oasa reservoir, aiming to create a reservoir at an elevation of 380 maSL with a volume of 27.4 GL. Despite the system's impressive technical specifications, including a gross head of 854 meters and a turbine power capacity of 3139 MW, the project's scale and complexity come with significant challenges. The high initial investment costs associated with such a large-scale system, along with the extensive infrastructure needed for its operation, make the implementation of this project financially unrealistic.

From an environmental perspective, the proposed facility would have considerable implications. Constructing large reservoirs and installing extensive pipelines may lead to habitat disruption, especially in the surrounding areas of Oasa Lake. Additionally, while the system is designed to improve energy efficiency, the environmental costs of construction, potential impacts on local biodiversity, and water management need careful consideration.

3.7.2. Plesi case study

The pumping facility analyzed involves taking a flow of 586 m^3/s from the Oasa reservoir and creating a reservoir at an elevation of 380 maSL with an area of 131 ha and a volume of 27.9 GL. Delimitation of the reservoir to be done by contour dykes with a height of 60.4 m [23].

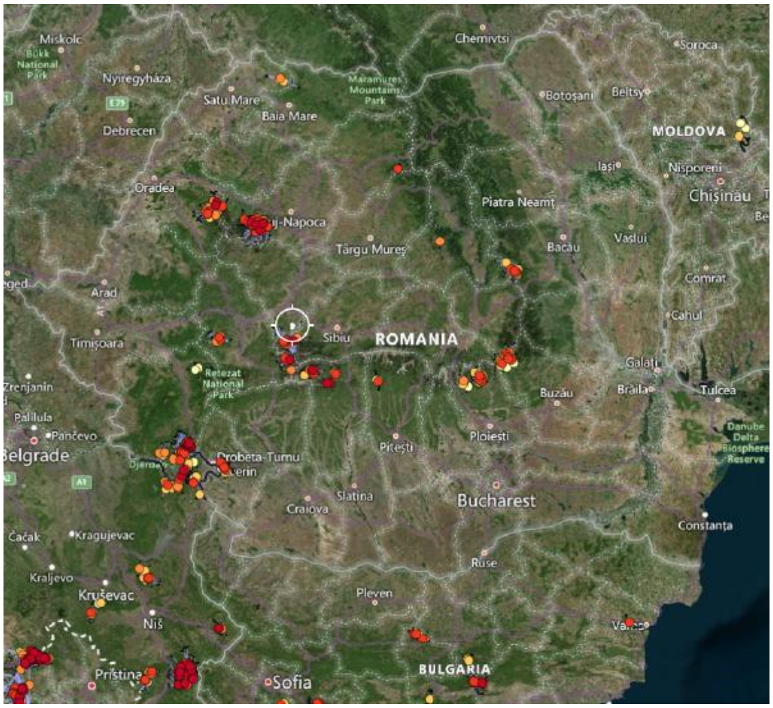


Figure 10- Oasa Lake: Plesi location (45°48'52.0"N 23°36'49.5"E)

Main technical characteristics:

• Upper reservoir: located at an elevation of 380 maSL, with a useful volume of approximately 27.9 GL of water and an area of 131 ha.

• Gross head: approximately 854 m.

• Pipe length: 21.8 km.

• Turbine power: 4064 MW.

• Pumping power: 6416 MW.

Operating parameters:

• Efficiency: overall efficiency at flow: 82.8%.

overall efficiency at pumping: 76.5%.

• Operating time: flow/pumping time: 10 hours.

• Installed flow rate: 586 m^3/s.

Energy consumption and production:

• Daily energy consumed: 64164 MWh.

• Daily energy produced: 40643 MWh.

Conclusion

The Plesi case study highlights the technical feasibility of a large-scale pumped hydro energy storage (PHES) system, with an installed flow of 586 m^3/s and a significant gross head of 854 m. However, the high costs associated with implementing such a system for this flow make the investment unrealistic from an economic perspective.

Beyond financial constraints, the environmental impact of the proposed reservoir and infrastructure must also be considered. The creation of a 131 ha reservoir would result in substantial land use changes, potentially affecting local ecosystems, biodiversity, and water quality. The construction of contour dykes reaching 60.4 m in height could disrupt natural drainage patterns and lead to habitat fragmentation. Additionally, the energy losses inherent in the pumping process (with an efficiency of 76.5%) mean that a portion of the consumed energy would be derived from external sources, potentially increasing the carbon footprint depending on the energy mix.

3.7.3. Cugir case study

The pumping facility analyzed involves taking a flow of 530 m^3/s from the Oasa reservoir and creating a reservoir at an higher elevation (approximately 330 m between the upper reservoir and Oasa lake) with an area of 98 ha and a volume of 26.4 GL. Delimitation of the reservoir to be done by contour dykes with a height of 54.6 m [23].

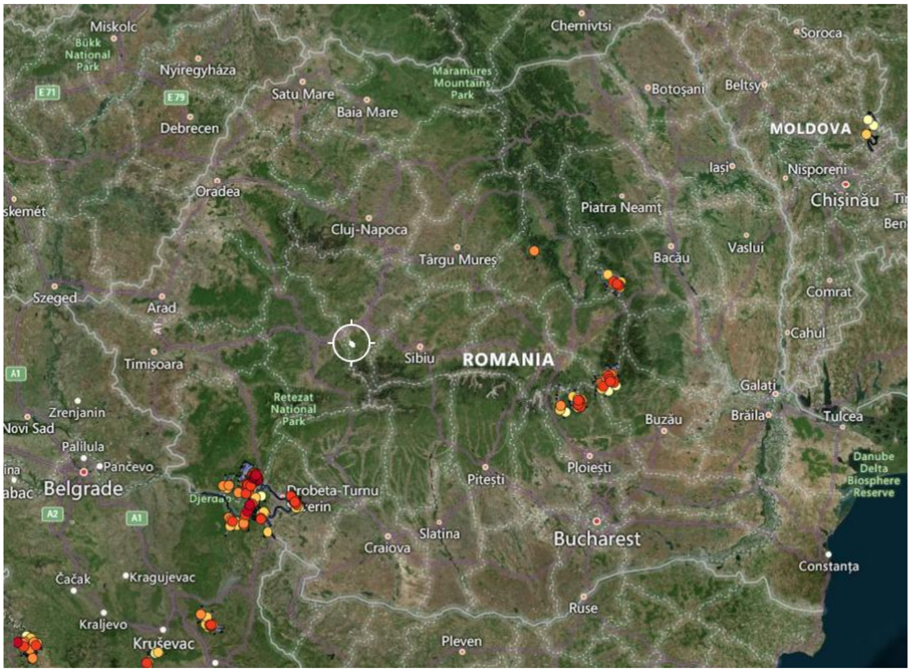


Figure 11- Oasa Lake: Cugir location (45°49'04.0"N 23°23'50.8"E)

Main technical characteristics:

• Upper reservoir: located at an elevation of 1566 maSL, with a useful volume of approximately 26.4 GL of water and an area of 98 ha.

• Gross head: approximately 904 m.

• Pipe length: 28.3 km.

• Turbine power: 3889 MW.

• Pumping power: 6140 MW.

Operating parameters:

• Efficiency: overall efficiency at flow: 82.8%.

overall efficiency at pumping: 76.5%.

• Operating time: flow/pumping time: 10 hours.

• Installed flow rate: 530 m³/s.

Energy consumption and production:

• Daily energy consumed: 61399 MWh.

• Daily energy produced: 38891 MWh.

Conclusion

The proposed pumping facility at Cugir involves a substantial installed flow rate of 530 m³/s, which presents significant technical and economic challenges. The high costs associated with infrastructure development, particularly at this scale, make the investment unrealistic. Additionally, the partial overlap with populated areas raises concerns regarding land use conflicts and social impact. From an environmental perspective, the project would lead to considerable landscape alterations due to the construction of contour dykes and the creation of the upper reservoir. Potential ecological disruptions include habitat loss, changes in local hydrology, and risks to aquatic ecosystems in Oasa Lake. Given these challenges, alternative locations with lower environmental and social impact, as well as improved efficiency metrics, should be considered for pumped hydro storage development.

3.8. Siriu case study

The studied location is in the vicinity of Zabratau, Romania, located in the Eastern part of Romania.

The pumping facility analyzed involves taking a flow rate of 740 m³/s from the Siriu reservoir and creating a reservoir at an elevation of 981 maSL with an area of 163 ha and a volume of 53.5 GL. Delimitation of the reservoir to be done by contour dykes with a height of 60.9 m [23].

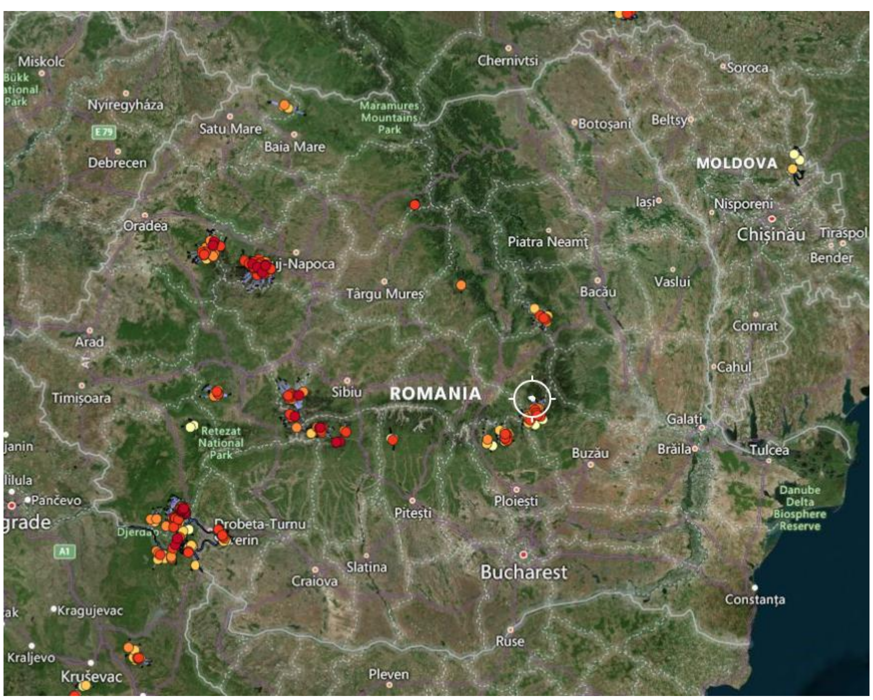


Figure 12- Siriu Lake location (45°39'14.9"N 26°11'41.4"E)

Main technical characteristics:

• Upper reservoir: located at an elevation of 981 maSL, with a useful volume of approximately 53.5 GL of water and an area of 164 ha.

• Gross head: approximately 447 m.

• Pipe length: 14.7 km.

• Turbine power: 2685 MW.

• Pumping power: 4239 MW.

Operating parameters:

• Efficiency: overall efficiency at flow: 82.8%.

overall efficiency at pumping: 76.5%.

• Operating time: flow/pumping time: 10 hours.

• Installed flow rate: 740 m^3/s.

Energy consumption and production:

• Daily energy consumed: 42393 MWh.

• Daily energy produced: 26853 MWh.

Conclusion

While the Siriu site offers significant hydro-pumping potential with a high installed flow rate, the feasibility of such a large-scale project remains questionable. The substantial costs associated with infrastructure development for a 740 m^3/s flow rate make the investment economically challenging. Additionally, geological concerns, including the restricted exploitation of the Siriu Dam and existing landslides at the tail of Siriu Lake, further complicate the placement of an upper reservoir. From an environmental perspective, the project raises concerns regarding land use, biodiversity, and water management. Constructing an upper reservoir would require significant land alterations, potentially impacting local ecosystems and habitats. Moreover, the energy losses during the pumping cycle and the alteration of natural water flow patterns could disrupt aquatic life and water quality. A thorough environmental impact assessment would be necessary to evaluate these risks and identify mitigation measures. Given the challenges outlined, alternative sites or scaled-down solutions should be considered to balance energy needs with environmental sustainability.

General conclusion regarding the potential of PHES development in Romania based on the case studies

Pumped Hydro Energy Storage has long been regarded as a crucial tool for balancing intermittent renewable energy sources, such as wind and solar power, with energy demand. While large-scale PHES projects, such as those exceeding 1000 MW, are often proposed as a solution to renewable energy integration, several factors make these projects less viable in Romania. This chapter examines these challenges, based on case studies and the broader experience of PHES development.

Large PHES projects, especially those with capacities over 1000 MW, present significant challenges. One of the most pressing issues is the geographical limitations in Romania. While the country has abundant mountainous regions, suitable locations for massive reservoirs and the necessary elevation differences are limited. Constructing such large-scale infrastructure requires substantial land, and the construction of large dams and reservoirs may encounter opposition due to land use, environmental concerns, and regulatory hurdles.

Additionally, the capital required for large projects is immense. The initial investment in infrastructure, including the construction of dams, reservoirs, tunnels, and turbines, can be prohibitively high. This long payback period makes large PHES projects less appealing, especially when compared to smaller, more cost-effective alternatives. The extended timeline for construction can also result in inflationary pressures and changes in the energy market that affect the economic feasibility of such projects.

4. High Energy Concentration is Not Ideal

High-capacity PHES plants, such as those over 1000 MW, concentrate large amounts of energy in a single facility. This concentration of power can lead to several problems. For example , it can destabilize the grid when the plant is either discharging or charging energy. A single large plant can create large fluctuations in energy supply, which may strain the grid and make it more challenging to balance supply and demand. Smaller PHES projects are more easily integrated into the grid without risking significant disruptions.

Moreover, the concentration of energy in one facility could lead to overproduction in certain regions, especially during periods of low demand. This oversupply can result in inefficiencies, as energy may need to be curtailed or diverted, creating operational challenges and increasing costs. Smaller plants, distributed across regions, can mitigate these issues by offering more flexible power generation and reducing the strain on any single part of the grid.

4.1. Pressure on the grid

Large-scale PHES projects, especially those with high capacities, place considerable pressure on the grid. Transmission losses become a significant concern when energy from large plants needs to be transported over long distances. These losses reduce the efficiency of the system, making the grid less reliable and raising operational costs. Moreover, large PHES plants can limit the operational flexibility of the grid. When one massive plant is relied upon, it becomes more difficult to adjust to sudden changes in demand or renewable energy output, potentially resulting in imbalances and operational difficulties [24].

Furthermore, the sheer size of such projects places strain on local transmission networks. If the PHES facility is far from urban centers, the local grid may struggle to handle the immense energy influx, leading to potential disruptions in power supply. Smaller, decentralized PHES plants can avoid this issue by distributing the energy storage capacity across multiple locations, enhancing grid stability and operational flexibility.

4.2. Economic feasibility

From an economic standpoint, large PHES projects are not always the best option. While the operational costs of PHES systems are relatively low, the upfront investment required for large-scale projects is substantial. With a lengthy construction period, the return on investment (ROI) for these projects is often slower compared to smaller projects. In Romania, where securing funding for large infrastructure projects can be challenging, the financial risk associated with large PHES plants may outweigh their benefits.

Moreover, the financial environment in Romania may favor smaller, more manageable projects. Smaller PHES systems can be completed faster, have lower initial costs, and offer quicker returns [7]. These advantages make them more attractive to investors and ensure a better economic balance for the country's energy market. Additionally, smaller projects carry less financial risk and can be scaled or adapted more easily to meet evolving energy needs.

4.3. Environmental issues

Large PHES projects also bring significant environmental concerns. The construction of vast reservoirs and extensive infrastructure can disrupt local ecosystems, especially aquatic habitats, and biodiversity. The environmental costs of such projects are not always adequately considered, especially when large amounts of land need to be cleared or transformed to accommodate reservoirs and dams. In Romania, where environmental regulations are stringent, large-scale PHES projects can face opposition from environmental groups and local communities.

In addition, the need for substantial water resources to fill large reservoirs can exacerbate existing water scarcity issues, especially in regions that already struggle with maintaining consistent water flow. The environmental footprint of large PHES projects can thus be much higher than smaller ones, where the scale of land use, water requirements, and habitat disruption are minimized.

4.4. Smaller PHES (maximum 300 MW) is considered to be a better solution

Considering the challenges discussed, smaller PHES projects, particularly those with a maximum capacity of 300 MW, present a more viable and sustainable solution for Romania's energy needs. The economic amortization of most power lines in Romania becomes considerably more challenging if they exceed this threshold. These smaller plants offer several advantages, including reduced environmental impact, lower initial costs, and faster construction timelines. The ability to integrate multiple smaller projects into the grid ensures better flexibility and stability, allowing for more efficient management of energy resources.

Smaller PHES systems are also better suited to integrate renewable energy, providing localized storage and balancing intermittent energy sources without overwhelming the grid. From an economic perspective, smaller projects are more financially feasible, offering quicker returns on investment and lower financial risk. Additionally, they can be scaled more easily to accommodate future energy needs, allowing for greater adaptability in Romania's evolving energy landscape.

In conclusion, while large PHES projects may seem attractive in terms of their scale and energy output, smaller systems are ultimately more suited to Romania's geographical, environmental, and economic conditions. The focus should shift towards decentralized, smaller PHES facilities (up to 300 MW) to enhance the country's energy security, integrate renewable energy sources more effectively, and ensure a sustainable, resilient energy future.

5. RheEnergise as an alternative solution

RheEnergise's innovative energy storage system, branded as High-Density Hydro, leverages a proprietary fluid, R-19™, which is 2.5 times denser than water. This higher density allows energy storage systems to be smaller and operate on much lower elevations (as low as 100 meters), compared to traditional pumped hydro storage which typically requires mountainous regions with elevations of 300 meters or more. The R-19 fluid is also non-toxic, non-corrosive, and engineered to reduce environmental risks. The system stores excess renewable energy during low-demand periods by pumping the fluid uphill between underground storage tanks, then releases it downhill through turbines to generate electricity during peak demand.

Advantages of RheEnergise Over Conventional PHES

Site Accessibility: Conventional PHES relies on steep elevation differences, limiting its deployment to specific geographies. RheEnergise's technology expands the range of potential sites by operating on smaller hills, unlocking thousands of new locations worldwide.

Construction and Environmental Footprint: RheEnergise's system uses underground tanks and requires 2.5 times less vertical space, reducing construction costs and minimizing environmental disruption compared to conventional PHES.

Energy Output: At equal elevations, the high-density fluid generates 2.5 times the energy of a traditional water-based system, improving energy density and efficiency.

Table 8. Technical and Economic Comparison

	Conventional PHES	RheEnergise High-Density Hydro
Working Fluid	Water	High-Density Fluid R-19 (2.5x denser)
Required Elevation	300 meters or more	100 meters or more
Energy Output	Standard based on water density	2.5 times higher for same elevation
Construction Footprint	Large reservoirs and dams required	Smaller underground tanks, minimal land impact
Cost	Higher due to large civil engineering needs	65% lower due to reduced size requirement
Site Availability	Limited to mountainous regions	Widely available across low-hill regions
Environmental Impact	High, with potential ecosystem disruption	Low, with less land and water usage

5.1. An added value to Pumped Hydro Energy Storage Systems

This fluid significantly enhances energy storage capacity without increasing the size of reservoirs or elevation. For example, a conventional water-based system requiring a 300-meter elevation can achieve equivalent energy output with RheEnergise's system at just 120 meters. The system comprises underground storage tanks at different elevations connected by pressurized pipelines. During periods of low-cost energy, typically generated by renewables, the R-19 fluid is pumped uphill. When demand peaks, the fluid flows downhill, spinning turbines to generate power.

Unlike traditional PHES, RheEnergise's technology is highly modular, with project sizes ranging from 5 MW to 100 MW, making it suitable for integration into existing renewable energy farms. It can also function in areas unsuitable for traditional systems, such as low hills and even subterranean spaces.

5.2. Environmental Impact

Conventional PHES often disrupts ecosystems, requiring significant land alteration and water resources. RheEnergise's underground, closed-loop system minimizes land and ecological impact, avoids water contamination, and aligns with strict environmental regulations. Additionally, the non-toxic, non-corrosive nature of R-19 reduces long-term environmental risks.

5.3. Economic Implications

5.3.1 Cost-Benefit Analysis

Traditional PHES projects, while reliable, involve substantial upfront investment due to large-scale infrastructure requirements. In comparison, RheEnergise systems leverage smaller infrastructure, reducing costs by up to 65%. The scalability of RheEnergise systems ensures that even small renewable energy farms can afford energy storage solutions, democratizing access to this critical technology.

5.3.2 Market Potential

RheEnergise estimates 6500 potential sites in the UK alone and over 500,000 globally, including regions in Africa, the Middle East, and North America. This vast market potential positions RheEnergise as a transformative force in renewable energy integration.

5.4. Real-World Applications

5.4.1 Field Trials and Demonstrations

In 2022, RheEnergise successfully conducted field tests in Canada, proving that its high-density system operates effectively at half the elevation of a conventional water-based system. This milestone demonstrated the scalability and economic viability of the technology.

5.4.2 Renewable Energy Integration

RheEnergise systems are designed for co-location with wind, solar, and bioenergy projects, enabling efficient energy storage and grid stability. The compact design allows seamless integration without requiring large tracts of land.

5.5. Environmental and Social Implications

Traditional PHES projects often face resistance due to environmental degradation and displacement of communities. RheEnergise addresses these concerns through minimal land use, underground infrastructure, and the use of environmentally safe materials. The ability to restore natural grasslands or reforest areas above its facilities further enhances its ecological appeal.

RheEnergise's High-Density Hydro offers significant advantages in terms of site accessibility, energy efficiency, and environmental sustainability. While traditional PHES remains effective for large-scale energy storage, RheEnergise's solution provides a more versatile and lower-cost alternative suitable for diverse geographic conditions. This flexibility is crucial as renewable energy adoption grows, requiring scalable and sustainable energy storage solutions.

6. Conclusions and Recommendations

The implementation of pumped hydropower in Romania represents a solution for optimizing the functioning of the National Energy System, in the context of the global energy transition towards renewable energy sources.

At European and global level, the increase in the share of intermittent renewable energy (wind and solar) requires the adoption of efficient energy storage solutions, and pumped hydropower plants are considered one of the most mature and reliable existing technologies.

Thus, solutions are needed for: making the energy system more flexible, integrating renewable sources, energy security and stability, reducing energy dependence, etc.

Pumped power plants allow the transfer of electricity from off-peak to peak periods, balancing energy demand and supply. This contributes significantly to the stability of the NES, especially in a context marked by the volatility of production from renewable sources.

PHES also supports the implementation of intermittent renewable sources, offering a long-term storage solution and compensating for their variability. In Romania, wind and solar energy potential can be exploited in optimal conditions only by complementing them with appropriate storage solutions, such as pumped storage plants.

A PHES plant provides emergency reserves, secondary and tertiary regulation, ensuring the stable operation of the NES in emergency situations. The "black start" capacity is crucial for restarting the system in the event of major failures.

By replacing gas-fired plants, pumped storage plants significantly reduce greenhouse gas emissions, supporting Romania's and the European Union's climate neutrality objectives by 2050, especially by adopting modern technologies, using the latest technologies in the design and operation of pumped storage plants, such as automation, digitalization and optimization of energy management systems.

Projects such as Tarnița-Lăpuștești should not be considered, given the national and European energy strategies context and the volatility and uncertainties regarding the evolution of energy prices, while the Colibita, Frasin-Pangarati and Socol projects, if approached correctly can have less impact on the environment, lower costs, produce more reliable and stable energy, with a still serious cumulative installed power contribution of over 500 MW.

Romania should capitalize on funding opportunities through European programs, such as the Modernization Fund or the Recovery and Resilience Fund, for the development of sustainable energy infrastructure, minimizing the ecological footprint by avoiding protected areas and water bodies with good ecological status. Also, given its strategic geographical position, Romania can become a regional energy hub, providing system services and supporting the interconnection of energy networks in Central and South-Eastern Europe.

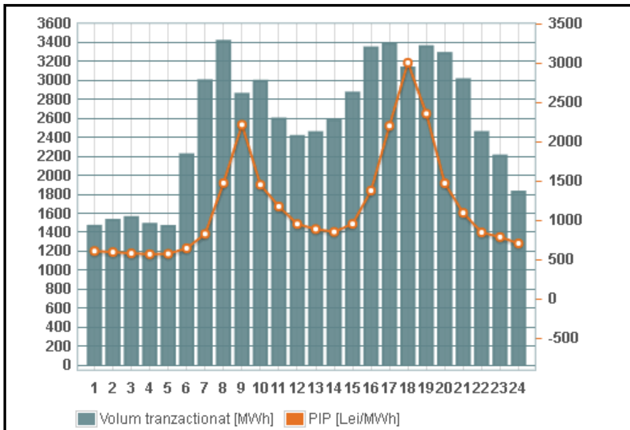
The cost-benefit analysis of pumped hydropower energy storage systems highlights their potential as a cornerstone of Romania's renewable energy transition. While the initial and operational costs are considerable, the long-term economic, environmental and social benefits make PHES an attractive investment. This analysis highlights the importance of strategic planning, transparent stakeholder involvement and the adoption of sustainable practices to maximize the benefits of PHES while minimizing its challenges.

It is therefore recommended to study and implement new PHES projects in locations outside protected areas, avoiding water bodies with good ecological status, with hydropower potential, both in mountainous regions and in areas with existing facilities, by modernizing and adapting them, as well as integrating pumped storage plants with other storage solutions by developing an energy mix based on the complementarity between pumped storage and new technologies, such as high-capacity batteries or green hydrogen.

An important component is the identification of solutions to increase the resilience of NES to climate change, PHESs can contribute to the efficient management of hydrological resources and to the mitigation of the effects of extreme phenomena, such as droughts or floods. An obligatory analysis is the environmental impact analysis of hydro-pumped energy storage systems, highlighting the complex interaction between energy development and ecological sustainability. In Romania, where the need for clean energy must be balanced with the preservation of diverse natural and cultural landscapes, careful planning and mitigation are essential.

In conclusion, the implementation of pumped hydropower energy storage (PHES) in Romania is a strategic solution for optimizing the National Energy System (NES) amidst the global transition to renewable energy. PHES addresses critical challenges such as energy system flexibility, integration of intermittent renewable sources and energy security. Projects like Colibita and Frasin-Pangarati, if executed with careful planning and minimal environmental impact, can significantly contribute to Romania's energy transition. Leveraging European funding opportunities and adopting modern technologies will further enhance the efficiency and sustainability of PHES. However, it is crucial to prioritize environmental preservation, conduct thorough impact assessments, and integrate PHES with complementary storage solutions to maximize its benefits. With strategic planning and stakeholder collaboration, PHES can serve as a cornerstone of Romania's renewable energy future, positioning the country as a regional energy hub while balancing ecological and energy development goals.

Appendix 1. The variation of prices in the market of the following day. Representative examples.



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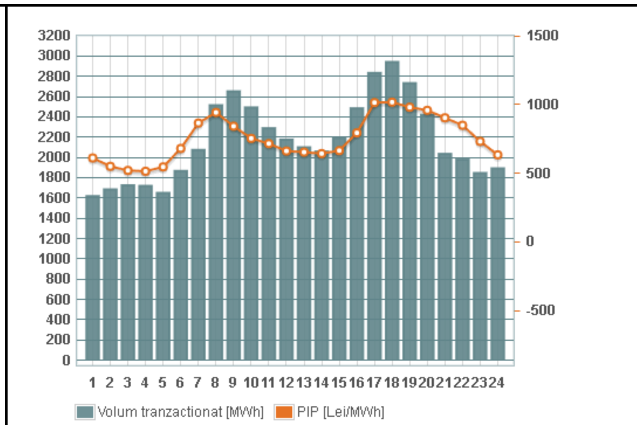

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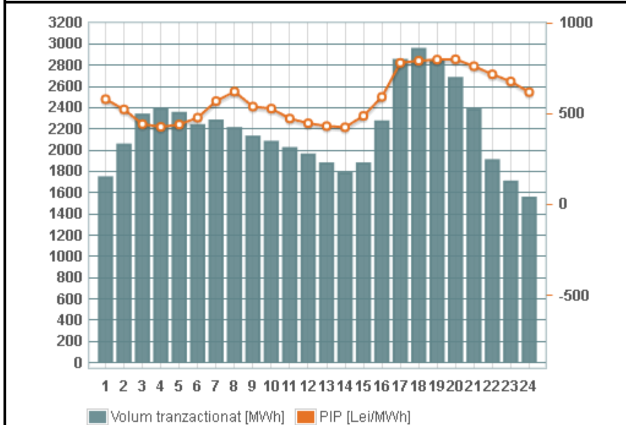

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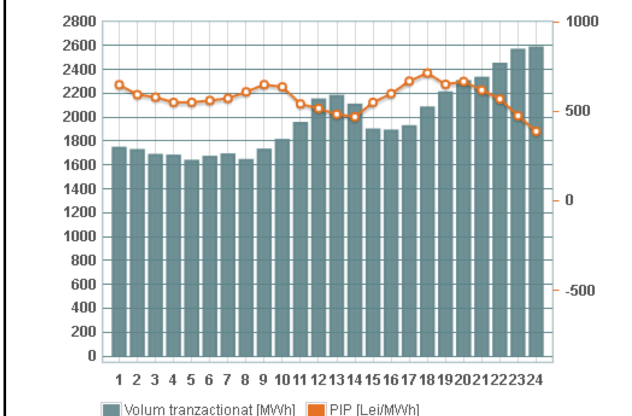

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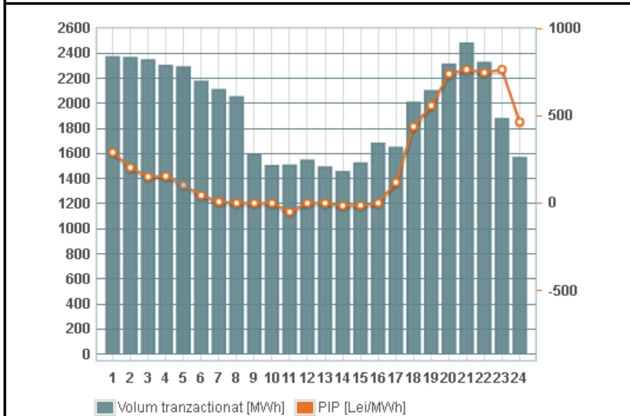

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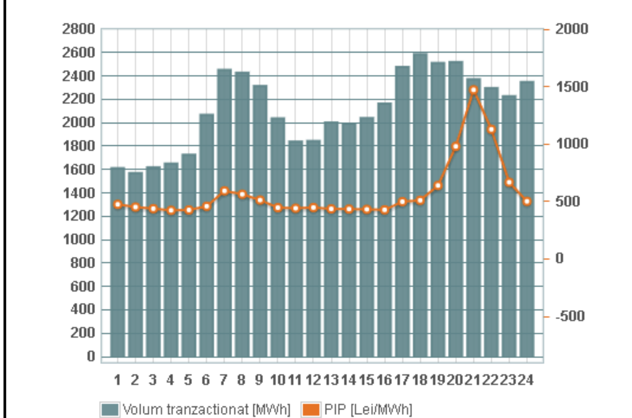

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