#NaturaEAcasa

Study on hydropower retrofitting potential in Romania

Dr. ing. Cornel Ilinca, dr. ing. Cristian Anghel, ing. Răzvan Puia, ec. Bogdan Ilinca

Contents

NOMENCLATURE

GWh – Gigawatt hour
MW – Megawatt
TWh – Terrawatt hour
E.U./EU – European Union
TES - Total energy supply
HPP - Hydropower plant
U.S. /US – United States
DOE - Department of Energy
WFD - Water Framework Directive
EIAs - Environmental impact assessments
ETS - Emissions Trading System
ARIMA – Autoregressive integrated moving average
GARCH – Generalized AutoRegressive Conditional Heteroskedasticity
MCDA - Multi-criteria decision analysis
ROI - Return on investment
INHGA - National Institute of Hydrology and Water Management
ANAR - National Administration Romanian Waters
CFD - Computational fluid dynamics
AI - Artificial intelligence
CF - Capacity factor
VRE - Variable renewable energy
BEP - Best Efficiency Point
FSFC - Full-Size Frequency Converter
RoR - Run-of-river
HDPE - High-density polyethylene
FDC - Flow duration curve
CBA - Cost-benefit analysis
IRR - Internal rate of return
NES – National energetic system
NPV - Net present value
OPEX - Operational expenditures
CAPEX - Capital expenditures
GHG - Global greenhouse gas
CDM - Clean Development Mechanism
SNGA - National Strategy for Water Management Romania
PNI - Integrated National Plan

Executive Summary

This study examines the potential for modernizing Romania's aging hydropower infrastructure to enhance electricity production, improve grid stability, and support national energy security. Hydropower remains Romania's largest renewable energy source, contributing to over a quarter of the country's electricity mix. However, many of its hydropower plants were built decades ago, with aging equipment limiting their efficiency and output. Retrofitting these facilities presents a cost-effective and environmentally sustainable solution, offering a faster alternative to new hydropower development while leveraging existing infrastructure.

The study estimates that modernization efforts could increase Romania's annual hydropower generation by 500–600 GWh under a low-ambition scenario, focused on incremental improvements such as pipeline relining and turbine repairs. A high-ambition scenario, involving comprehensive upgrades like advanced turbine replacements and digital automation, could boost production by 800–1,100 GWh—representing a 7% increase in hydroelectric output. This additional generation could replace electricity imports, reinforcing Romania's energy security and reducing reliance on external power sources.

Beyond energy gains, retrofitting enhances grid flexibility, enabling hydropower to balance variable renewable energy sources like wind and solar. Modernized plants equipped with real-time monitoring and predictive maintenance can provide essential grid services such as frequency regulation, stabilizing Romania's power supply. Economically, retrofitting can be 40-50% cheaper than constructing new plants, making it the most viable strategy to expand renewable generation capacity.

From an environmental perspective, retrofitting minimizes disruption by optimizing existing facilities rather than building new dams. Modernization measures such as fish passage solutions, sediment management, and ecological flow regulations help maintain biodiversity while improving plant efficiency. Unlike new projects, which can fragment river ecosystems, retrofitting aligns with European environmental policies and avoids additional greenhouse gas emissions.

Prioritizing high-potential sites, such as hydropower plants along the Bistrița River, could yield the greatest energy and economic benefits. By acting swiftly to implement targeted retrofits, Romania can strengthen its energy independence, accelerate renewable energy growth, and achieve a more resilient, low-carbon electricity system.

The technical work for this study was carried out by Senior Lecturer PhD Eng Cornel ILINCA.

The completion of this report was also made possible through the collaborative efforts of Diana Cosmoiu, Adam Harmat, Andreea Danciu, and Raluca Șerbănică.

1. Introduction

Romania has a diversified energy mix. In 2022, coal, 80% locally extracted, provided 14% of the primary energy mix; crude oil and petroleum products (approx. 65% imported, 35% domestically produced) approx. 36%; natural gas (approx. 84% from domestic production, 16% imported) approximately 30% of the mix; renewable energy and biofuels approx. 12%, and nuclear energy approx. 9%. The diversity of the energy mix has allowed the NES (National Energetic System) to maintain its resilience, overcoming stress situations. The situation of extreme temperatures related to the specificity of the regions, when the NES is subject to vulnerabilities in ensuring the full coverage of energy demand for both domestic consumption and export, the situation also present in neighboring states. Between 22.09.2017 and 01.06.2023, capacities totaling an installed power of 5,508 MW were withdrawn from operation in Romania. Thus, in 2023, the installed capacity in the electricity system reached a historical minimum of 18,254 MW [1].

In 2023, the structure of Romania's net installed electricity capacity reflected a moderate diversification of sources. Hydropower dominated with a share of 36%, followed by natural gas (16%) and wind energy (17%). Renewable sources included solar (8%) and biomass/biogas 1%, while nuclear energy contributed 8%. The distribution still indicates a strong dependence on conventional sources (coal and gas), which account for over 30% of the capacity. Progress in the renewable sector is visible, especially in wind and solar, but it lags behind the country's potential. Special mention deserves the growth of bioenergy, which highlights the efforts to transition to more sustainable sources. However, the development of the sector requires accelerated investments to balance the energy mix and reduce emissions. In terms of energy produced, it is noteworthy that the share similar to the difference of nuclear energy increases to 20%, while hydro, wind and solar energy decrease depending on the capacity factor [1].

The increase in energy generation and other benefits that may be associated with modernization of existing capacities is of great interest, especially if we consider that the modification of existing plants may be free from most of the environmental impacts and conflicts related to the construction of new hydropower plants (HPPs) on pristine and unregulated rivers (river sections). Modernizing the existing HPPs would consolidate and further improve current energy generation and grid flexibility, i.e., hydropower capacity to adapt its operating conditions within a short time and support ancillary services, while extending the lifespan, addressing operational issues, increasing the level of safety, and reducing environmental impacts. In this report, we propose a screening-level, large-scale quantification of the gains in terms of annual generation and flexibility that the modernization of the Romanian hydropower fleet might yield. We investigated different modernization practices applied at the European and US scale, considering the hydropower fleet characteristics and including all the hydropower plant types (reservoir and run-of-river). For each practice, we propose an indicator of the additional energy generation that can be expected and the potential contribution it may bring to Romania. We discuss our results considering statistical factors, economic indices and also some legislative and environmental reality checks.

Hydropower modernization may lead to retrofitting, upgrading, or/and refurbishing of plants. Retrofitting consists of using recent technologies to improve plant performance, such as control schemes, fault protection, digitalization and monitoring, automation of some auxiliary equipment, and even changing some parts of important equipment, thus improving efficiency [2]. Upgrading implies changing the main equipment (turbines, generators) and the infrastructure (dam height, intakes) [3]. Refurbishing represents the repair and/or replacement of old equipment, which also requires significant civil works for increasing, for instance, safety and predictability.

Done right, hydropower offers energy, water, proven technology, a long-life span, flexibility, reliability, and national economic stimulation. Hydropower offers significant potential for carbon emissions reductions [4].

Negative impacts arise from socio and environmental changes, including resettlement and loss of livelihoods, heritage, biodiversity, water courses, and fisheries. The intent of the methods discussed in this study is to ensure that benefits are maximized, and negative impacts are avoided, minimized, mitigated and compensated.

Important environmental issues encompass habitat loss, biodiversity loss, invasive species, water quality, methane emissions, erosion, reservoir sedimentation, and downstream flow regimes. Reservoir sedimentation can greatly limit the life of a hydropower project and can be exacerbated by catchment practices beyond the control of the hydropower facility. Passage of aquatic species past the physical barrier presented by dams has been a challenge for the hydropower industry. Increasingly with climate change, reliability of the water resource and avoidance of greenhouse gas emissions from reservoirs need careful consideration [5].

This study will expand on the methodology and calculations underpinning these estimates. A detailed analysis will identify the specific hydropower plants that require urgent retrofitting based on various scenarios, such as low-ambition refurbishment and high-ambition retrofitting and upgrades. Additionally, a screening-level assessment will outline the potential candidates for pumped-storage retrofitting. This expanded section will incorporate background information, modeling techniques, and scenario-based results to provide a comprehensive and transparent foundation for the outcomes presented in this study.

Thus, this study will focus on hydropower plants with installed power of at least 10 MW, in conformity with EU classifications.

2. Alignment with European and Global Sustainability Policies and Social benefits

Beyond the domestic context, the European Union has set ambitious targets for renewable energy deployment and greenhouse gas emissions reduction. Hydropower refurbishment aligns with these objectives, offering a viable pathway for Romania to contribute to Europe's energy transition [7].

The UN Conference on the Human Environment in Stockholm marked a turning point in global environmental awareness in 1970. It recognized the interconnectedness of environmental issues and human activities and laid the groundwork for international cooperation on environmental protection. In 1972, the UN Conference on the Environment in Stockholm further emphasized the importance of environmental protection and introduced the concept of ecodevelopment. Ecodevelopment emerged as a response to growing environmental concerns and promoted economic development compatible with environmental protection and social equity.

The Brundtland Commission's report, "Our Common Future," introduced the widely accepted definition of sustainable development in 1987. This definition highlighted the balance between economic growth, social development, and environmental protection. In 1992, the Earth Summit in Rio established the framework for global sustainable development, producing the Rio Declaration on Environment and Development and the Agenda 21. The World Summit on Sustainable Development in Johannesburg reaffirmed the commitment to sustainable development and addressed specific challenges such as poverty, energy, and water. It also emphasized the importance of corporate social responsibility and public-private partnerships.

The concept of corporate social responsibility gained prominence in 2010, recognizing the role of businesses in promoting sustainable development by integrating social and environmental concerns into their operations. In 2015, the UN General Assembly adopted the 2030 Agenda for Sustainable Development, which included a dedicated and stand-alone goal on energy, SDG 7. This goal calls for ensuring access to affordable, reliable, sustainable, and modern energy for all. Energy lies at the heart of both the 2030 Agenda for Sustainable Development and the Paris Agreement on Climate Change. Achieving SDG 7 will open up a new world of opportunities for millions of people through new economic opportunities and jobs.

The European Union has set a clear policy direction through its Green Deal and Clean Energy Package, which aim to make Europe the first climate-neutral continent by 2050. Hydropower retrofitting in Romania must be closely aligned with these overarching goals to ensure both compliance and the maximization of benefits. A key policy driver is the Renewable Energy Directive (RED II), which sets binding targets for the share of renewable energy in the EU’s energy mix. Romania, like all member states, is required to contribute to the EU-wide target of 32% renewable energy by 2030. By retrofitting its hydropower plants, Romania can significantly increase the share of renewable energy in its energy mix, while also ensuring grid stability.

Another important piece of legislation is the European Water Framework Directive (WFD), which establishes stringent environmental standards for water bodies across Europe. The directive aims to achieve "good status" for all EU water bodies, meaning that hydropower retrofits must be carefully designed to minimize ecological impacts. Romania will need to strike a balance between maximizing hydropower output and protecting aquatic ecosystems. Fish passage solutions, improved sediment management, and optimized water flow regimes must all be incorporated into retrofitting strategies to ensure compliance with the WFD. Environmental impact assessments (EIAs) and ecological monitoring will also be essential for ensuring that retrofitted plants operate sustainably.

The EU Emissions Trading System (ETS) is another important consideration for Romania's hydropower sector. While hydropower plants themselves do not emit greenhouse gases, retrofitting projects may have indirect impacts on emissions, particularly if they involve extensive construction activities. Romania will need to assess the lifecycle emissions of retrofitting projects and explore ways to minimize their carbon footprint. For example, using low-carbon materials in turbine replacement or adopting green construction practices could reduce the overall environmental impact of these projects. Moreover, by increasing hydropower capacity, Romania could reduce its reliance on fossil fuels and lower its participation in the ETS, contributing to overall emissions reductions in line with EU goals.

Retrofitting Romania's hydropower plants is not just a technical and environmental challenge; it also presents social opportunities. Retrofitting can improve the resilience of local communities by providing a more stable and reliable energy supply. Hydropower plants are often located in remote, underserved regions where energy security is a major concern. By retrofitting these plants, Romania can ensure that these communities have access to a reliable source of electricity, reducing the likelihood of power outages and contributing to regional development. In addition, the environmental benefits of hydropower retrofitting—such as reduced emissions and improved water management—can enhance the quality of life for residents in these areas, who are often the most affected by environmental degradation and climate change.

3. Hydropower plants in Romania

To understand the importance of hydropower, first the fundamental principles of hydroelectric power generation and the equations involved in converting the potential energy of water into electrical energy that are used to calculate the potential energy of water and the power that can be generated from a hydroelectric power plant must be explained, key concepts such as specific energy, head, mechanical work, power and also the components of a typical hydroelectric power plant can be found in Appendix C [8].

3.1. Data collection

The database used for this study (table from Appendix 1) contains data on various hydroelectric power plants (HPPs) in Romania. The database provides information such as: unique identifier for each HPP, county and nearest municipality where the HPP is located, technical details (type of HPP, installed power, fall, and other technical specifications), year of commissioning, number and type of turbines, average output, and other operational metrics.

Based on the information available in the table, the data can be used to analyse hydroelectric power production capacity and efficiency (203 records, see Appendix 1).

Many hydropower projects are evaluated in isolation of an overall basin planning framework, and issues arise due to competing or conflicting needs and uses of the basin resources. Integrated Water Resource Management has a focus on understanding and rationalizing the use of and impacts on basin resources. With respect to hydropower, this may result in measures to ensure maintenance of ecosystem services (e.g. fish passage or sediment through-flow), protection of developed river reaches, more coordinated operation of different hydropower facilities to achieve better water resource efficiencies, delivery of environmental flow regimes, and/or increased multipurpose hydropower facilities to offer a variety of services such as irrigation, water supply or aquaculture [12].

3.2. Data analysis
The use of mathematical models is necessary to project the energy production in the future, according to different scenarios of hydropower sector retrofits. These can be done from multivariate statistical analyses (such as factor analysis or principal component analysis) to identify key factors influencing production, to time series models (ARIMA, GARCH) to analyse the time evolution of hydropower production, this being generally used on a hydroelectric plant where average monthly energies and average monthly flows are known. A simple analysis of hydroelectric energy over the last ten years shows that it is uneven by quarter with a production of approximately 30% in the second quarter and 20-25% for the rest of the quarters, this being the result of flow lamination due to accumulations (dams).

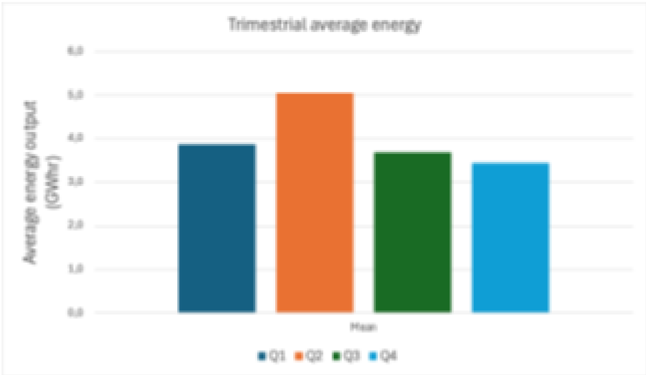

Figure 4. Quarterly average energy for the last 10 years [12].

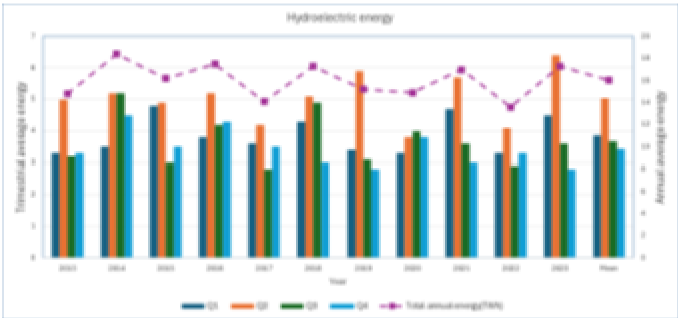

Figure 5. Quarterly average energy for the last 10 years [13].

The average annual energy has important variations from minimum quarterly energies below 3 TWh for quarter IV to over 6 TWh for quarter II, this being the result of the variability of the hydrological regime which is very high. Because of climate change and the increasing share of intermittent renewables, this variable regime will intensify. From this analysis it is noted that an increase in the efficiency of and a change in the operating mode of the hydroelectric plants will bring an increase in the production of electricity.

3.3. Multivariate statistical analysis
The multivariate statistical analysis is a collection of statistical techniques that allow us to explore the relationships between several variables simultaneously.

Direct proportionality between the installed hydroelectric energy and the average annual energy production is highlighted. This bond is important for understanding Romania's hydropower potential and for making economic decisions regarding the upgrade in the energy sector. The analysis was performed for a linear and a polynomial correlation, the interpretation was chosen for the linear correlation.

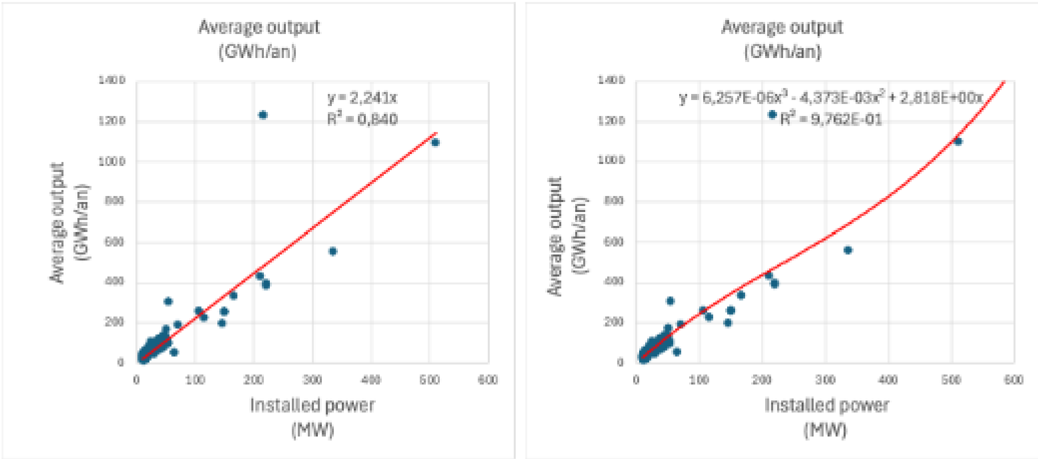

Figure 6. Average energy depending on the installed power (left – linear correlation; right parabolic correlation).

The slope of 2.24 indicates that average annual output increases by approximately 2.241 GWh for every 1 MW increase in installed capacity. This linear relationship suggests a relatively consistent efficiency of the analyzed hydropower plants. In addition to the installed power, there are other factors that influence energy production, such as:

- Hydrological regime: River flow, seasons, climatic variations can significantly affect energy production.
- Maintenance: The operating condition of the equipment and the frequency of maintenance can influence the efficiency of the hydropower plant.
- Efficiency of the turbines: In general, the turbines are old and their yields are 4-5% lower than at commissioning due to wear.
- Energy price: Fluctuations in the price of electricity can affect the profitability of hydropower plants.

It is noted that points above the regression line should be the first candidates for increasing turbine power, including by increasing the efficiency of turbines such as Portile de Fier II.

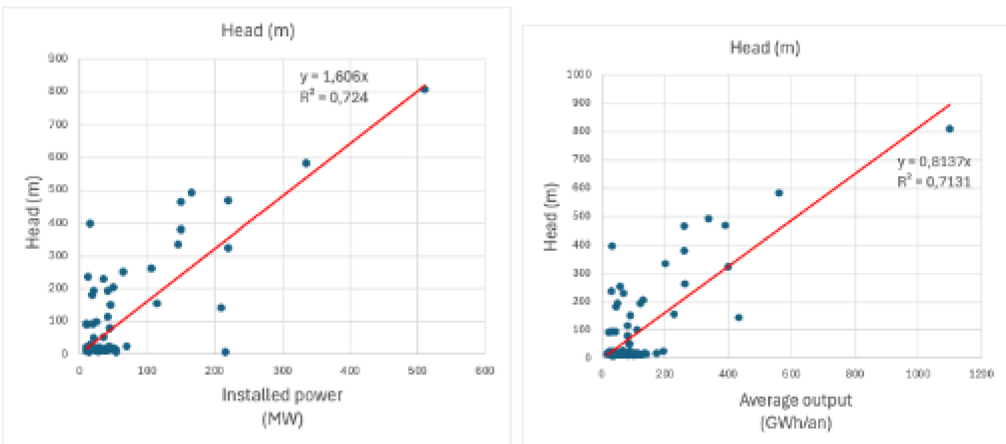

Figure 7. Head as a function of installed power (left) and the Head as a function of the average output (right).

The annual average energy versus installed power graph shows a linear relationship between the installed power of a hydropower plant and the water fall. Hydroelectric plants with a higher head generally require lower investment by increasing the efficiency of the turbines, so points above the straight line may be an optimal choice for turbine retrofitting, except for large hydroelectric plants such as Portile de Fier II, whose retrofitting is based on the increase in installed power discussed previously.

3.4. Prioritizing hydropower plant upgrades: A criteria-based approach.
In order to modernize the hydropower potential of hydropower plants (over 10 MW), in order to achieve an increase in electricity by approximately 7% of the average annual energy, an action plan is necessary that mainly includes the criteria for prioritizing the modernization of the respective hydropower plants.

The criteria are technical-economic, social and environmental and can have a multi-criteria decision analysis or probabilistic approaches.

A multi-criteria decision analysis (MCDA) approach is generally required to prioritize the upgrading and rehabilitation of HPPs, this involves assigning weights to each criterion and scoring each HPP according to the criteria. HPPs with the highest global scores would be prioritized for rehabilitation.

i. Technical and economic criteria. These are defined by technical analysis regarding the technical condition of the objects, the Potential Energy Gain and the Estimated Cost of Rehabilitation realized through Cost-benefit analysis of potential rehabilitation projects and Return on investment (ROI) and payback period. This includes HPP's operational flexibility to adapt to changing energy demand and grid conditions.

- The state of hydropower units determined by age and efficiency (turbines, generators, drives and automation) is a criterion by which the technological advance over time is recognized but also the deterioration that leads to decreases in hydropower performance and including the availability of hydroelectric plants. For this, equipment condition evaluation reports are required based on the maintenance history and the records of the electricity produced on each individual hydro unit.

- The state of the pipelines and other works (water intakes, etc.) is a criterion that is determined not only by the inherent uses of these but also by the materials and technologies used in the past, which can be improved today. For example, for pipelines, they can shrink water losses and hydraulic load losses through relining by the tight in pipelines method or epoxy resins, polyurethane, and polyurea coatings.

- The state of the electricity transmission system, especially the need to increase the transmission capacity. This is one of the main reasons for the national dispatcher interrupting electricity production capacities due to the insufficient power of electrical transformers or the transmission capacity of electrical lines.

ii. Impact on the environment and socioeconomic criteria. Environmental impact is presented here with socioeconomic impact, as many times the inherent benefits and drawbacks of large dams and hydroelectric plants are correlated.

- Potential environmental impacts resulting from rehabilitation activities, this criterion is very important because hydroelectric energy which is renewable also aspires to the status of green energy, which is debatable because in general large hydroelectric plants with reservoirs create a major impact through emissions of greenhouse gas from the anaerobic processes in the depth of the reservoirs, the interruption of the longitudinal and lateral connectivity of the rivers, the interruption of fauna mobility from one bank to the other due to the reservoir, the drastic reduction of the downstream flow with a major impact on the ichthyofauna and the transformation of a water course into a lake with all the severe consequences for the biotope. For example, it must be specified that additional construction works, such as raising dams in protected areas and of community interest, are prohibited.

- Compliance with European and national environmental regulations and standards, this is a criterion that generally should not be stated, but in Romania, a deregulation initiated by the Romanian state, and a non-compliance with its own legislation is observed. For example, HG 148/2020 had clear implementation deadlines imposed by the Romanian state, which were also violated by the authorities subordinate to the Romanian state. Another example is the authorization of works to finalize some hydroelectric investments that violate all the environmental regulations also approved by the Romanian state. Another example is the conflict of interests of some entities like the National Administration Romanian Waters (ANAR) that check and monitor the salubrious/ecological flow defectively, their interest being to use as much water as possible for the holders of hydropower capacities because the water that is paid for constitutes part of ANAR's funds. Another example is the National Institute of Hydrology and Water Management (INHGA) which, with the support of ANAR, approves, through diffuse and unclear provisions, new uses and users of water (trout farms, etc.), thus increasing the pressure on water bodies.

- Opportunities to improve the environment and reduce the socio-economic impact on local communities downstream of large dams, through the creation of passages for ichthyofauna or other measures such as the imposition of clearer regulations on the ecological flow and the flow of downstream water users. A reregulating reservoir, situated downstream of a peak hydropower plant, is essential for storing fluctuating discharges and releasing them in accordance with environmental flow requirements.

Dams affect the longitudinal and lateral connectivity of rivers. The disruption of longitudinal connectivity limits the mobility of species in their habitats and leads to biodiversity loss. In addition, the modification of hydrogeomorphological processes and the hydrological regime affects rivers and alters habitats, including the riparian zone, with negative implications for biodiversity and the functioning of lotic ecosystems. The modified hydrological regime downstream of dams is characterized by a prolonged period of anthropogenic hydrological drought (approximately eight months per year), which, combined with the effects of climate change, accentuates the negative impact on the environment. Given the importance of the problems regarding the longitudinal connectivity of rivers in the field of hydrotechnical developments and constructions and their implications in improving the ecological status of surface water bodies, it is essential to identify solutions for the design of fish passes in the retrofitting process of hydroelectric power plants. The presence of dams and weirs in protected natural areas, some of national interest, others of community interest, and others of international interest, requires the integration of updated fish passes. In conclusion, the retrofitting of hydroelectric power plants must also address this environmental requirement.

In addition to these criteria, for assessing the global hydropower retrofit potential, probabilistic approaches can offer significant advantages, particularly in handling uncertainties and variations in input values.

iii. The usual statistical analysis is done using histograms that have the relative frequencies on the ordinate (y) or cumulative curves that have the cumulative frequencies on the ordinate (y) (cumulative curve). Cumulative frequencies will be used in the present analysis, since it is easy to determine in which percentile a certain value falls, and in the analysis of distributions, data distributions can be compared.

The percentiles (P) represent the data set values related to the total number of hydropower plants expressed as a percentage. Percentiles measure which values of a data set fall below a certain percentage of the total number of points. The empirical probability (percentiles, P) will be calculated using Hirsch's formula, $P_i = \frac{i+0.5}{n+1}; i = 1..n$, having the property that it has the same median value as Anon's formula $P_i = \frac{i}{n}$, the maximum value approaches the Landwehr formula $P_i = \frac{i-0.35}{n}$, and the minimum value is below the value given by Laplace's formula $P_i = \frac{i+1}{n+2}$, these being practically identical in terms of the analyzed records number [14].

In the analysis of the modernization of the power plants, different criteria can be used in which recommendations are made on a statistical basis, for example by establishing quartiles (Figure 8). This is necessary to prioritize the modernization of hydropower plants that would bring important energy gains by modernizing in principle a small number of units with large installed powers, but also those hydropower plants that have a low installation coefficient, thus having a net capacity factor, $CF_i = \frac{E_m}{P_{installed} \cdot yr}$ as high as possible.

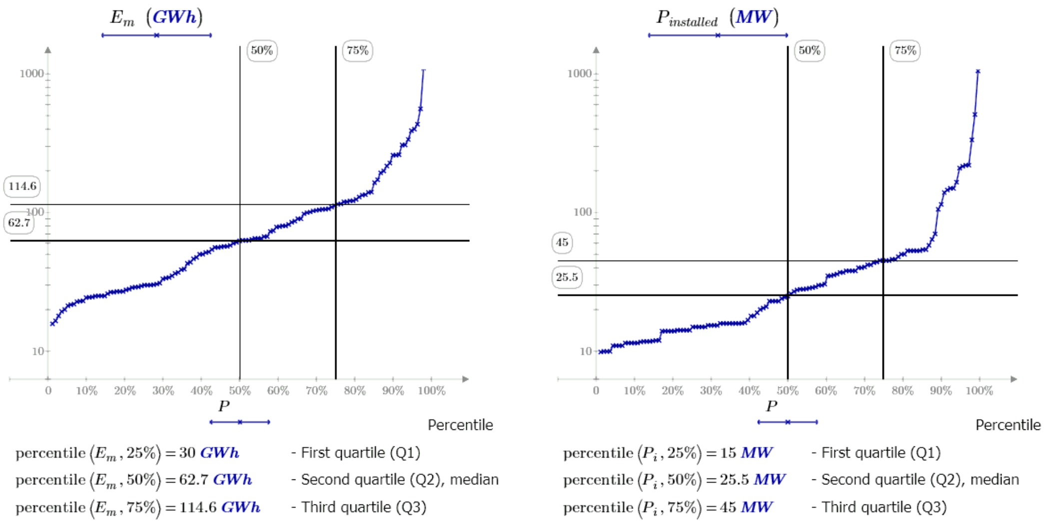

Figure 8. Chart highlighting the quartiles.

The recommendation to focus retrofitting efforts on plants with power and energy outputs above the third quartile (Q3) is based on the following reasoning:

- 75% of the plants have capacities below 45 MW. Retrofitting plants above this threshold would target a significant portion of the higher-capacity plants, potentially yielding substantial energy gains. Plants with higher capacities often have more potential for efficiency improvements through retrofitting.

- Lower-capacity plants (below Q3) may not benefit as much. Namely, these plants already operate at lower power levels, and retrofitting them might not significantly increase their output.

- Lower-energy hydropower plants (below 114.6 GWh) might have limited retrofitting potential. A thorough cost-benefit analysis should be conducted to evaluate the economic feasibility of retrofitting each hydropower plant.

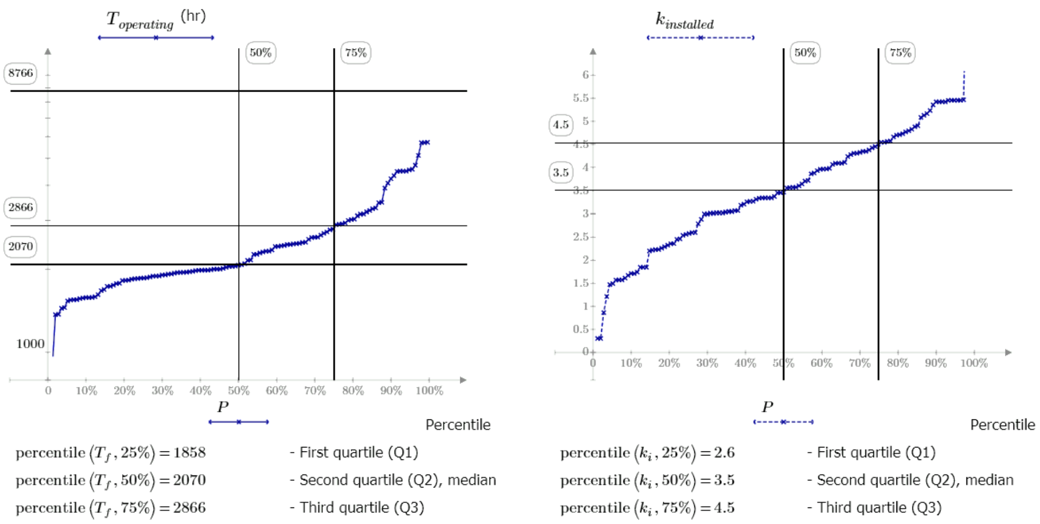

Figure 9. The distributions of average operating time.

The two graphs in Figure 9 depict the distributions of average operating time at installed power (T) and installation coefficient (ki) for hydropower plants in Romania with capacities exceeding 10 MW.

The recommendation is to focus retrofitting efforts on plants with operating time above the third quartile (Q3) and installation coefficient below the median (the middle value when a data set is ordered from least to greatest).

This means 75% of plants operate less than 2866 hours. Targeting plants above this threshold would focus on those with higher utilization, potentially yielding significant energy gains through retrofitting. Plants with higher operating times often have more potential for efficiency improvements through retrofitting.

Lower operating time plants (below Q3) might have limited retrofitting potential. Their lower utilization might be due to factors other than capacity, making retrofitting less impactful.

The installation coefficients of hydropower plants under the median value have installation coefficients below 3.5. Retrofitting plants below this value would target those with lower installation costs, potentially making the retrofitting more cost-effective. Plants with higher installation coefficients (above the median) might have higher retrofitting costs.

Targeting plants with operating times above the third quartile and installation coefficients below the median aligns with the goal of maximizing energy output and optimizing the use of existing hydropower resources. However, it is crucial to consider the specific characteristics of each plant and conduct a comprehensive assessment to determine the most effective retrofitting strategies.

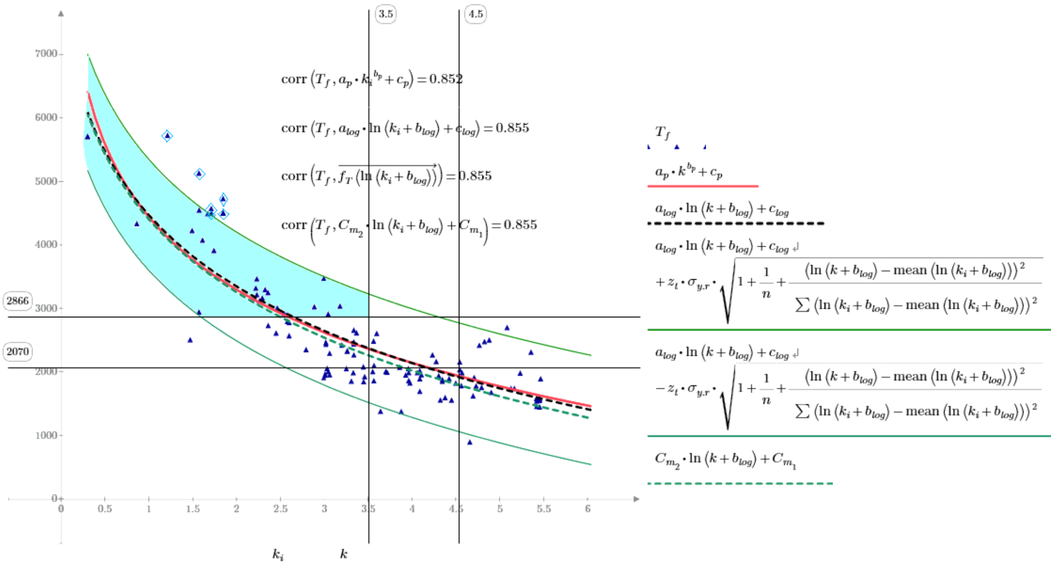

Figure 10. The correlation between the installation coefficient and the operating time.

In the attached graph (Figure 10) is the power and logarithmic correlation between the installation coefficient and the operating time at the installed power. Parameter estimation by the methods of least squares and median-median regression was used. The confidence interval of the logarithmic regression was calculated, and the recommendation is made to modernize the hydropower plants whose installation coefficient is below the median value, and the operating time values at the installed power are in the area delimited by the graph of the limits of the confidence intervals.

The recommendation to modernize hydropower plants with an installation coefficient below the median and operating time within the confidence interval is based on the optimal principle, which could improve their efficiency and increase operating time. By focusing on plants within this interval, we can be more confident that modernization will lead to significant improvements in operating time.

While the installation coefficient and operating time are important factors, other factors like the age of the plant, maintenance history, and local hydrological conditions can also influence the potential for improvement. Modernizing older plants can also lead to environmental benefits.

The average yield of hydropower plants larger than 10 MW from the design data is 80% and the median value is 81.7%, these being small values. This yield refers to the efficiency of the equipment, specifically the ability of turbines and generators to convert water energy into electricity under ideal conditions. It is not the same as the capacity factor, which measures the actual energy output over a period as a percentage of the maximum possible output. Capacity factors for hydropower plants are typically much lower, ranging between 30% and 50%, depending on factors such as water availability, operational schedules, and environmental constraints.

3.4.1. Scenario Analysis

The low-ambition scenario focuses on preserving the functionality of existing hydropower plants through targeted, cost-effective refurbishments. This approach prioritizes basic repairs to turbines and control systems, as well as measures such as pipeline relining to reduce head losses. By addressing the aging infrastructure of smaller hydropower plants, such as those along the Bistrița River, this scenario aims to achieve incremental energy gains of approximately 500 to 600 GWh annually. While these improvements may not revolutionize energy output, they provide a practical and relatively low-cost pathway to enhance performance and reliability.

The high-ambition scenario takes a more transformative approach, aiming to maximize energy output and efficiency through comprehensive modernization efforts. This includes the upgrade of key components such as turbines and generators, alongside the implementation of advanced digital control systems. Large-capacity hydropower plants are prioritized for these upgrades, given their significant potential for increased generation. Energy gains under this scenario are estimated to range between 800 and 1100 GWh annually, representing a substantial contribution to Romania's renewable energy goals. Such a strategy requires greater investment but delivers long-term benefits in terms of both energy production and system efficiency.

In addition to these scenarios, retrofitting pumped-storage capabilities offers a strategic opportunity to enhance energy storage and grid flexibility. By equipping plants with dual-purpose turbines and making reservoir modifications, existing hydropower facilities could play a pivotal role in supporting the integration of intermittent renewable energy sources like wind and solar. Plants such as Colibita and Lotru-Ciunget are potential candidates for these retrofits, with operational gains varying depending on specific scenarios. This approach aligns with broader energy transition efforts, ensuring that the hydropower sector contributes not only to generation but also to the stability and adaptability of the energy grid.

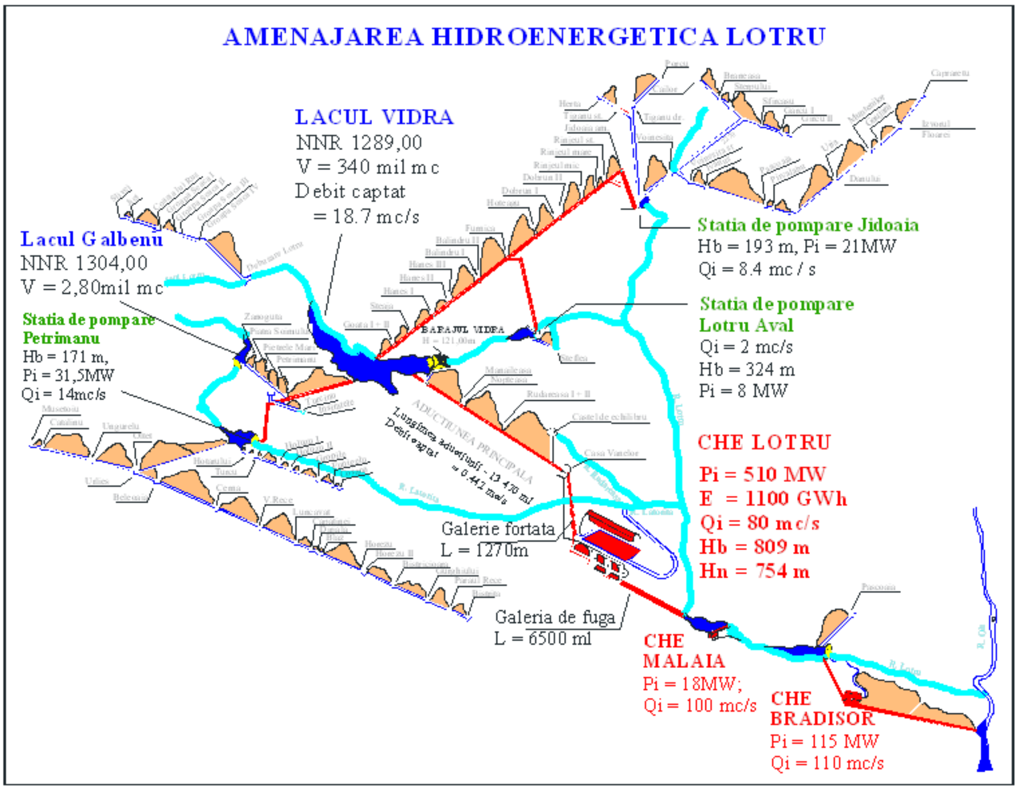

Figure 11. Lotru Hydropower Development.

3.4.2. Identifying Candidate Hydropower Plants for Retrofitting, Refurbishment, and Pump-Storage Upgrades

Scenario Analysis and Candidate Selection

Based on the table in Appendix 1, several hydropower plants emerge as strong candidates for various upgrades. These selections are influenced by factors such as current capacity, operational age, potential for increased output, and suitability for pump-storage technology. Some examples:

Low-Ambition Scenario: Targeted Refurbishments

- Smaller Hydropower Plants Along the Bistrița River: These plants, while smaller in scale, collectively represent a significant opportunity for incremental gains. By addressing basic maintenance needs like turbine repairs, control system upgrades, and pipeline relining, these facilities can significantly improve their efficiency and reliability. This scenario aligns with a cost-effective approach to enhance the performance of existing infrastructure.

High-Ambition Scenario: Comprehensive Modernization

- Bistrita: These plants, being larger than the other Bistrita River plants, could benefit from a more comprehensive modernization approach. Upgrading its turbines and generators, as well as implementing advanced control systems, could lead to a 15-20% increase in energy output, translating to an additional 200-300 GWh annually.

- Arges: These plants, with its substantial capacity, is a prime candidate for modernization. Investing in advanced technologies and infrastructure upgrades can optimize its performance and maximize energy production, potentially leading to a 10-15% increase in output, or an additional 300-450 GWh per year.

Vidraru HPP, located on the Argeș River, harnesses energy over a 28 km stretch and stands as one of Romania's key hydroelectric installations. At its inauguration, the Vidraru Dam was the fifth tallest in Europe and the ninth globally, with a height of 317 meters and a length of 678 meters. The plant has an installed capacity of 220 MW and produces an average annual output of 3508 GWh.

The retrofitting of the Vidraru Hydroelectric Power Plant (HPP) aims to:

- Increase the active power of each hydro unit from 55 MW to at least 58.8 MW while maintaining the maximum discharge flow rate of 22.5 m^3/s per unit (90 m^3/s total).

- Enhance the efficiency and overall yield of the plant.

- Improve performance and return on investment beyond initial levels.

- Boost reliability, availability, and operational safety of equipment and facilities, ensuring high-quality system services.

- Introduce a centralized monitoring and control system linked to the national energy dispatcher (DEN) for operational flexibility.

- Prepare the plant's equipment and facilities for a new operating cycle.

● Jiul: Similar to Arges, the Jiul plants offer significant potential for increased energy output through modernization. Upgrading its turbines, generators, and control systems can enhance its efficiency and reliability, potentially leading to a 12-18% increase in output, or an additional 350-500 GWh per year.

● Dambovița-Clabucet: This plant, with its relatively high capacity, could also benefit from completion efforts. Implementing advanced technologies can lead to increased energy production and improved operational efficiency, potentially leading to a 100% increase in output, or an additional 50-60 GWh per year.

Pump-Storage Retrofitting

● Lotru-Ciunget: While not explicitly mentioned in the table, the Lotru plants could be considered for pump-storage retrofitting, depending on its specific characteristics and the feasibility of reservoir modifications. This could increase their energy storage capacity and flexibility, allowing it to better integrate with renewable energy sources.

● With complex and potential adaptations of suitable existing reservoirs a conservative energy increase estimate would be in the range of 50 to 150 MW. This reflects a scenario where existing infrastructure is leveraged with moderate modifications.

Additional Considerations and Potential Candidates

● Other Plants such as Colibița, Izvorul Muntelui-Bicaz, PF I (Orșova), with Suitable Reservoir Conditions: Hydropower plants with existing reservoirs that can be adapted for pumped-storage operations should be evaluated on a case-by-case basis. If Romania pursues dedicated new PHES projects in optimal geological locations, alongside significant upgrades to existing facilities, the potential could reach 500-600 MW, in the case of least impact of the environment.

Conclusion

By strategically implementing these upgrades, Romania can significantly enhance the performance and value of its hydropower sector. The low-ambition scenario provides a practical and cost-effective approach to address the needs of smaller plants, while the high-ambition scenario unlocks the full potential of large-scale facilities. Pump-storage retrofitting, in particular, can contribute to a more resilient and flexible energy system by enabling the storage of excess renewable energy for later use.

If hydroelectric plants with efficiencies lower than the median value are modernized and there is an overall efficiency increase of 8%, an increase of 530 GWh would be obtained.

If the decision is made to modernize the power plants using the criterion of installed power higher than the third quartile (45 MW) or Q3 energy (115 GWh), an energy increase of approximately 1100 GWh will be obtained.

If the decision is taken to modernize the plants using the operating time criterion at the installed power higher than the third quartile (2866 hr), an energy increase of approximately 790 GWh will be obtained.

If the decision is taken to modernize the power plants using the criterion of the installation coefficient lower than the first quartile (2.6), an energy increase of approximately 800 GWh will be obtained.

The decision to modernize the power plants using the criterion of the installation coefficient lower than the median value (3.5) will bring an energy increase of approximately 960 GWh for 31 hydropower plants.

4. Technical assessment

The technical assessment of hydropower retrofitting in Romania involves a comprehensive analysis of the country's aging infrastructure, technological upgrades necessary for improving efficiency and reliability, and the engineering challenges associated with integrating these retrofits into the existing energy grid. Many of Romania's hydropower plants were developed after the mid-20th century, meaning much of this infrastructure has aged, with several plants nearing or exceeding their designed operational lifespans. While these plants have been vital to the country's energy needs, they now require modernization to meet contemporary energy demands, align with environmental regulations, and integrate seamlessly into a renewable energy mix that increasingly relies on intermittent sources such as wind and solar power.

The operational lifespan of hydropower equipment, such as turbines, generators, and auxiliary systems, typically ranges from 30 to 50 years, depending on maintenance practices, operating conditions, and technological advancements since their installation. Over time, the efficiency of older turbines can decrease by 5–10% due to wear, cavitation damage, and outdated design. Generators and control systems also face insulation degradation, reduced cooling performance, and mechanical fatigue, further lowering overall plant efficiency.

Key indicators signaling the need for modernization include: frequent breakdowns, increased maintenance costs, reduced energy conversion efficiency, and the inability to meet grid demands for flexible operations, a pronounced variability of flows, especially the emphasis on hydrological drought trends, thus requiring the adoption of technologies that can effectively manage these fluctuations and variability. A probabilistic analysis can also be performed to substantiate the decision to modernize the turbines, thus providing a more detailed perspective on the uncertainties that characterize the main factors that influence this decision, such as: the current efficiency of the turbine, as well as the potential for improvement; conducting trend analyses regarding the water resource; the cost of modernization and maintenance; the price of electricity, etc. Thus, a mathematical model/computational method (Monte Carlo, Bayesian Networks, etc) can be developed that realizes the interdependence of these variables, with a significant number of possible scenarios. This way, it can be established, for example, how the uncertainty of the energy price influences the viability of the modernization; what impact does a possible reduction of the water flow by a certain percentage have, etc.

Modernizing such components, with advanced materials and technologies, can restore efficiency, extend equipment lifespan, and improve the plant's adaptability to fluctuating hydrological conditions and renewable energy integration.

Upgrading turbines and generators forms the backbone of retrofitting efforts. Older turbines, such as the Francis, Kaplan, or Pelton types still operating in Romania, often function below optimal efficiency due to wear and outdated designs. Replacing these with modern high-efficiency models that use advanced materials and computational fluid dynamics (CFD) modeling can significantly enhance energy output while minimizing water usage. Such upgrades are particularly crucial in Romania, where seasonal and climate change-induced variations in water availability can disrupt power generation. Variable-speed generators, another significant technological innovation, allow plants to optimize performance during fluctuating flow conditions, ensuring reliable electricity generation under both high and low inflow/head scenarios.

Control systems in older plants often rely on outdated manual or semi-automated technologies, presenting inefficiencies in operation. By integrating advanced digital control systems capable of real-time monitoring and optimization, hydropower plants can more effectively respond to changing water availability and grid demands. These systems can manage turbine speeds, water flows, and generator output with precision, enhancing overall efficiency and reducing wear on equipment. Moreover, digitalization enables hydropower plants to provide ancillary services such as frequency regulation and voltage support, which are essential for stabilizing a grid increasingly reliant on variable renewables.

Ancillary systems such as intake structures, spillways, and penstocks also require attention. Intake structures may suffer from sedimentation and debris buildup, reducing water flow efficiency. Retrofitting with self-cleaning mechanisms or automated debris removal systems can mitigate these issues and reduce manual maintenance. Similarly, upgrading spillways to handle higher water volumes addresses the challenges posed by climate change, which increases the likelihood of extreme weather events. Penstocks, which channel water from reservoirs to turbines, often experience corrosion and wear over time. Replacing or refurbishing these structures with high-strength steel or composite materials can reduce leaks, improve water delivery, and lower maintenance costs.

Romania's participation in the European internal energy market is another critical consideration in the retrofitting process. The European Union has set ambitious targets for cross-border electricity flows as part of its strategy to create a unified and resilient energy market. Hydropower retrofitting in Romania should align with these goals, ensuring that retrofitted plants can export electricity to neighboring countries or import power during times of low generation. This requires not only upgrading physical infrastructure but also improving Romania's digital grid management systems to monitor and control electricity flows efficiently across national borders.

In addition to mechanical and electrical upgrades, digital technologies such as predictive maintenance systems and artificial intelligence (AI) solutions can further enhance the long-term operational viability of Romania's hydropower plants. Predictive maintenance uses real-time monitoring and advanced algorithms to identify potential equipment failures before they occur, reducing downtime and repair costs while increasing overall availability. AI systems can also optimize water flow management, forecast energy production, and ensure compliance with environmental standards, further boosting the economic viability of retrofitted plants.

Finally, environmental and regulatory considerations play a crucial role in retrofitting efforts. Romania's hydropower plants must comply with national regulations and European Union directives such as the Habitats Directive, Birds Directive, and Water Framework Directive (WFD). This may require additional technical measures, such as installing fish ladders or bypass systems to facilitate aquatic species migration and implementing sediment management systems to prevent reservoir buildup. Ensuring alignment with these requirements not only minimizes environmental impacts but also supports Romania's broader commitment to sustainable energy development within the EU framework.

To analyse potential solutions, the basic annual energy generation equation is decomposed so that the proposed solutions can be directly linked to a variable influencing energy production.

The annual energy generation of a hydropower plant can be calculated using the following equation [2]:

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

where:

- E (kWh), represents the annual generation,
- ρ, is the water density (1000 kg/m^3),
- g, is the acceleration due to gravity (9.81 m/s^2),
- Q, is the usable discharge (m^3/s),
- H, is the net head (m),
- η, is the efficiency of the power plant equipment,

including the hydraulic efficiency of the conduit (pipe)

- t, is the average annual duration of plant operation.

Another important metric in this analysis is the capacity factor (CF), which is the ratio of annual energy production to the energy that would be generated if the plant operated continuously at its nominal capacity. For instance, the average capacity factor in Europe is 0.35 (excluding pumped hydro), though it varies between countries—e.g., 0.26 in Romania and 0.5 in Norway [69,70].

Modernization strategies for hydropower plants focus on optimizing different elements of the equation. Some aim to increase the usable discharge (Q-strategy), others target increasing the net head (H-strategy), improving efficiency (η-strategy), or maximizing the operational time (t-strategy).

A Q-strategy may involve either increasing the total annual inflow (volume) or concentrating the flow during peak demand hours while keeping the annual inflow unchanged. Boosting the annual inflow is only feasible where climate change is expected to increase natural water discharges, such as in Norway [71]. However, much of Europe, particularly the Alpine region, is predicted to experience reduced annual flows due to glacier retreat [70, 73, 74]. In other locations, water protection laws usually limit additional withdrawals, making this approach site-specific. Therefore, the focus is often on concentrating flow during shorter periods of operation without increasing overall inflow. This strategy may require upsizing runners, improving waterway capacity, and adding hydraulic structures to prevent damage, all of which come with costs [75, 76]. These investments are justified if they enhance the plant's flexibility, enabling it to meet peak energy demands with increased installed capacity while cutting generation during times of surplus variable renewable energy (VRE) and reducing spills during high waters (hydrological regime). Potential Q-strategies also include installing floating PV systems to reduce evaporation, minimizing head losses in waterways, and improving flow management through digitalization, such as optimizing multi-unit operations. However, it is important to note that these strategies may lead to significant fluctuations in water levels downstream, particularly in the lower part of the river. Such fluctuations can negatively affect aquatic ecosystems, disrupt sediment transport, and impact water-dependent activities, such as agriculture and fisheries. To mitigate these impacts, measures like maintaining ecological flow requirements, constructing reregulation reservoirs, and implementing advanced flow scheduling can be incorporated into the Q-strategy. These steps ensure that while energy production is optimized, the downstream river environment remains stable and sustainable.

The η-strategy addresses the growing demand for turbine designs that perform efficiently over a wide range of operations, from part-load to full-load conditions. Current research focuses on improving overall efficiency across this range, known as weighted efficiency, rather than just at the Best Efficiency Point (BEP) or specific part-load values [77].

The t-strategy seeks to increase annual operational hours by minimizing downtime and maintenance, automating more functions, improving performance during transient conditions, and shortening the duration of start-stop cycles.

Lastly, the H-strategy mainly involves reducing head losses in waterways and, in some cases, increasing dam height, though the latter is highly site-dependent.

The main types of hydroelectric power plants analyzed in the paper are run-of-the-river and conventional hydroelectric multi-year regulated dams with reservoirs.

4.1. Dam heightening

The heightening of existing dams can be achieved with minimum increase of the heights (the height of the dams should be increased by approximately 5-10% of their existing height.) for the following reasons [2]:

▪ the provision of an appropriate safety guard, possibly to compensate for exploitation settlements in order to obtain the initial safety guard.

▪ ensuring a temporary elevation of the level in the lake during extreme floods with higher maximum flows than those considered in the original project, due to the updating of hydrological calculations with a more extensive data set, or due to climate change, keeping the initial value of the normal level of retention.

The heightening of existing dams can be achieved with substantially higher heights for the following reasons:

▪ obtaining useful volumes that were affected by the clogging of reservoirs.

▪ changing the accumulation coefficient which represents the ratio between the useful volume of the reservoir lake and average annual tributary stock [78];

▪ ensuring additional volumes of water in the lake to meet the increased water requirements for irrigation, domestic and industrial consumption, energy production, etc.

▪ increasing the degree of regularization or its duration curve, this being defined as the ratio between the minimum regularized flow ensured by the operation of the reservoir and the average multi-annual tributary flow;

▪ increasing the head coefficient for hydropower;

The last three are of particular interest in the field of hydropower.

The technical conditions necessary to heightening the existing dams, consist of:

▪ knowledge of the behaviour of the existing dam that does not present atypical fenomens;

▪ a configuration of the old dam that can withstand the increase in efforts due to the elevation of the dam;

- the assessment of the hydrostatic pressure distribution, the hydrodynamic pressure from the earthquake at the over-elevation of the dam and the effect of their increase on the foundation-dam assembly [79];

- knowing the behaviour of the foundation without presenting anomalies;

- the ability of the structure to transfer the forces of the elevated part;

- the tightness of the extended reservoir is guaranteed without any risk of sliding of the lake shores or the generation of large exfiltrations;

- a high quality index of the accumulation, it represents the ratio between the total volume of the reservoir and the volume of the dam body. It only applies to volume increases in the case of over-raising dams.

Economic conditions also become important in the context of the economic crisis; therefore it is necessary to follow the indicator regarding the specific volume investment for hydropower use, defined as the ratio between the investment in accumulation and the accumulated volume useful for hydropower use, in addition to other economic indicators of efficiency.

Based on current dam trends this is an unrecommended solution for hydropower for the following reasons:

- the increase in the level in the reservoir achieves the occupation of larger areas, thus resulting in the loss of habitats, thus a reduction of biodiversity;

- permanent or temporary flooding of some land surfaces, leads to the release of greenhouse gases due to anaerobic processes in the submerged soil;

- increasing the water surface leads to increased eutrophication, i.e. to an excessive enrichment of water with nutrients, which results in symptomatic changes such as the excessive production of algae and/or other aquatic plants, the deterioration of water quality with an impact on the aquatic fauna in the lake and a downstream of it.

- negative effects through expropriations, which can also affect socio-economic objectives, the landscape and elements of cultural heritage;

- the increase of the phreatic level with an impact on the chemistry of underground and surface waters through their natural drainage in watercourses.

- increasing the thermal stratification by increasing the water depth in the reservoirs, this being a characteristic phenomenon of deep lakes in warm periods, and represents a division of the water into layers with different temperatures: the epilimnion (surface layer, warm), the metalimnion (intermediate layer, with large temperature variations) and the hypolimnion (deep, cold layer). This stratification has significant implications for water quality and, implicitly, for ecological/healthy flow downstream of reservoirs.

The use of water resources for the production of electricity must be done in accordance with the requirements regarding environmental protection, imposed by various European directives, an aspect in which Romania has demonstrated numerous inabilities, such as the current desire to simplify administrative processes, calling doubtful compliance with the principle "not to cause significant damage" to the environment, which in reality turns out to be an unbalanced and superficial environmental approach of the environmental impact assessment.

The lack of hydrological studies regarding climate changes that affect the availability of water resources and may impose new challenges for the hydropower sector, is another problem for Romania.

4.2. Digitalization and inflow forecast

The collection and processing of real-time data to adapt the operating conditions of hydraulic turbines can offer advanced grid balancing services without compromising reliability and safety. In addition to enhancing predictive maintenance, which extends the equipment's lifespan, reduces downtime, and mitigates cybersecurity risks, rehabilitation and digitalization can increase overall efficiency and energy production. Betti et al. (2019) estimated cost savings between €25,000 and €100,000 over eight months at a 1000 MW hydropower plant in Italy, which utilized Francis-type pump-turbines, by preventing unplanned shutdowns [80]. Effective instrumentation for monitoring dams and hydroelectric units is described by Yanmaz and Ari (2011) and Silva et al. (2009). Moreover, machine learning can significantly enhance system health, guide maintenance, and optimize operations by implementing forecasting tools and predictive models that analyze the behaviour of hydropower components during steady-state and transient operations [81, 82].

Over time, turbine performance can drift from optimal efficiency due to changes in the hill chart, meaning machines may not operate at peak efficiency for a given head and discharge. For example, a study on a Kaplan-Bulb runner within the XFLEX HYDRO project (2021) showed that applying machine learning methods to operational data and feeding it into an optimization algorithm can recalibrate CAM curves, resulting in a 2% increase in energy production. The efficiency varies depending on the blade opening (adjustable runner blades) for each guiding vane opening (wicket gates). Every guide vane opening has a maximum efficiency point. By joining all the optimal efficiency points, a cam curve is created that shows the ideal ratio of guide vane opening to blade opening.

Digitalization also significantly reduces the response time of hydro units, particularly reversible pump-turbines. XFLEX HYDRO (2021) presents the Z'Mutt pumped storage plant case, where a 5 MW reversible pump-turbine with variable speed technology, powered by a Full-Size Frequency Converter (FSFC), improved response time through numerical simulations, reduced-scale model testing, and optimized operating sequences. Digital twins of hydropower plants can prevent failures and assess the economic impact of offering additional reserve flexibility. The cost of implementing a predictive system at a hydropower plant is approximately €200,000 [83]. Further optimization could be achieved using software based on genetic algorithms, such as EASY [84].

Transfer functions representing the dynamic behaviour of the hydraulic system components (reservoir, penstock, surge tank, turbine, and generator) have been used to improve plant flexibility and stability [85].

Digitalization can also improve fishway management by assessing the effects of hydrological variability on fishways, identifying operational problems, and optimizing their performance. Proper transient modeling, crucial for turbine governing systems, is essential for the safety and stability of hydropower plants. Accurate mid- and short-term flow forecasts are also vital for better water management and production optimization [86, 87].

4.3. Floating Photovoltaic (FPV)

Several factors highlight the benefits of coupling photovoltaic (PV) plants with hydroelectric power stations, as examined by various researchers [88].

The hybrid system of floating PV (FPV) and hydropower offers several advantages. One key benefit is that artificial hydropower reservoirs are already equipped with power generators and connected to the grid, reducing the associated costs for FPV compared to land-based installations. Additionally, FPV helps smooth out power fluctuations, particularly in temperate non-alpine regions where the panels produce maximum energy during the hot season, a time when hydropower output may decrease.

Another significant advantage is that FPV does not occupy land, avoiding conflicts with other land uses. Moreover, partially covering water basins with FPV panels reduces water evaporation, saving between 1,500 and 2,000 cubic meters per hectare of FPV [89].

On the environmental side, FPVs come with some potential concerns such as the disruption of bird habitats, particularly for species that rely on water bodies for feeding, nesting, or migration. The installation of FPV systems reduces the open water surface available to these birds, potentially displacing them from important areas. There is also a risk of collisions, as birds may mistake the reflective solar panels for water, leading to accidents, especially in low-visibility conditions. For fish, FPV systems can alter the aquatic environment by shading the water surface, reducing light penetration, which can affect photosynthesis in aquatic plants and subsequently impact the food chain. This could lead to changes in the availability of food for fish, as well as altered water temperatures and dissolved oxygen levels, both of which are critical for maintaining healthy fish populations. Similarly, shading from FPV installations can affect insect populations that depend on sunlight for their life cycles, and those insects, in turn, serve as food for both fish and birds. While FPV systems offer an innovative solution for renewable energy, their ecological impacts on birds, fish, and insects must be carefully studied and managed to minimize environmental disruption.

4.4. Start and stop improvement

The integration of intermittent energy sources into the current electricity market has introduced variability in grid operations, leading to frequent load variations, emergency shutdowns, restarts, total load rejections, and off-design operation of grid-connected hydraulic turbines. The number of start-stop cycles per day or year is determined by grid requirements, market decisions and hydrological conditions, rather than by the equipment owners. Existing pumped hydro storage (PHS) systems are now operating with more frequent start-stop cycles and fewer total generation hours, making revenues less predictable and reducing the financial viability of future projects [90]. While flexible technologies that reduce pressure loading on turbine blades during transients are more beneficial for extending turbine lifespan than for energy production, variable speed technology offers a way to reduce the frequency of start-stop sequences [91, 92].

Each start-stop cycle can reduce the refurbishment interval by up to 15 hours. Although turbine start-stop cycles cannot be entirely avoided, the runner's lifespan can be improved by minimizing harmful pressure loads on the blades during transients through strategic adjustment of the guide vanes. High-head Francis turbines can experience over 3,000 transients annually, and while reducing ancillary services could decrease the number of start-stop cycles, that is not the focus of current studies.

Base-load Francis turbines typically operate within a high-efficiency range, averaging only 1-2 start-stop cycles per year. However, peak-load units may undergo up to 10 start-stop cycles per day to maintain grid stability. Start-stop cycles can potentially cut the predefined refurbishment time by 50%. Additionally, a single start-stop can wear down the runner as much as several years of full-load operation [93, 94, 95].

Proposed changes in startup procedures can reduce damage, enhance reliability and extend lifespan, and ultimately help generate more energy [2].

4.5. RoR: increase of installed power (new and/or additional machines) at turbines

Turbine equipment is typically upgraded every 30 years [96]. Despite the challenges associated with rehabilitation projects, installing a newly designed runner within existing turbine structures can boost power output by 10 to 30%, thanks to improvements in efficiency and the potential for increased discharge due to a larger runner size. A comprehensive survey in Norway found that average increases in maximum power output were 18% for Francis turbines, 21% for Pelton turbines, and 21% for Kaplan-Bulb turbines [97]. These findings align with Goldberg and Espeseth Lier (2011), who reported potential output improvements of up to 30%, with additional discharge, while considering cavitation limitations based on unit settings. These improvements were largely achieved by increasing flow rate, expanding the runner’s outlet diameter, and adjusting flow angles. However, the gains in installed power are generally most effective around the best efficiency point and at full load [98].

For older run-of-river (RoR) plants built before 1960 on large streams, turbine discharge capacity is typically exceeded by inflows for around 150 days or more each year. When upgrading such plants, as seen on the Rhine and Aar rivers, the trend is to increase capacity to allow the plant to handle inflows except for 60 to 75 days per year. This helps avoid spilling water over the weir during the wet season, thus generating additional energy. For example, the Laufenburg power plant on the Rhine River underwent rehabilitation between 1985 and 1995, replacing its ten original horizontal-axis Francis turbines with ten new Straflo propeller turbines. This upgrade increased the turbine discharge capacity from 1025 m^3/s to 1420 m^3/s, which is only exceeded for about 60 days per year. As a result, annual production rose from 490 GWh to 630 GWh, a 29% increase [99].

Similarly, the Augst-Wyhlen RoR plant on the Rhine was rehabilitated between 1988 and 1994, replacing 11 old Francis turbines with 13 new Straflo propeller turbines. This upgrade boosted annual production from 250 GWh to 410 GWh (64%), with turbine discharge exceeding only 50 days per year [100, 101]. However, in many cases where turbine discharge capacity was significantly increased, costly rebuilding of powerhouse structures and weirs was necessary. One such example is the Rheinfelden RoR power plant on the Rhine, where the powerhouse and weir were replaced from 2003 to 2011. This upgrade increased nominal power from 26 MW to 100 MW and annual generation from 185 GWh to 600 GWh, with inflows exceeding turbine capacity for 300 days per year in the old plant [102]. This was an extreme example requiring a complete plant reconstruction and substantial investment.

In contrast, more modest interventions on infrastructure could increase the installed power of RoR plants built before 1960, potentially boosting production by 5% to 20%, depending on the flow duration curve. This additional generation during seasonal high flows would be particularly beneficial, as PV generation tends to be lower during bad weather.

4.6. Reduction of head losses in waterways and penstocks

Methods to minimize hydraulic energy losses can be found by starting with Manning's or Strickler's formula for computing linear pressure losses (distributed losses) in pipes. In hydraulic engineering, this formula is frequently used to calculate the energy lost as a result of fluid-wall friction.

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

- (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). The loss reduction methods for hydropower additions are:

- **Reduce pipe roughness:**

  o Reduce pipe roughness by relining. Smoother surfaces like epoxydic resin (or High-density polyethylene HDPE) can significantly reduce friction losses.

- **Optimize pipe geometry**

- Uniform cross-sections that avoid sudden changes in cross-sectional area, which can cause turbulence and increase losses.
- Use gradual curves or transitions between different pipe sections to minimize flow disturbances.

By implementing these measures, hydropower adductions can be designed and operated to minimize linear load losses, thereby improving overall system efficiency and maximizing energy production.

A reduction of the roughness in waterways and penstocks can also lead to an increase in power. Indeed, penstocks and waterways reduce their performance over the years due to increased friction and consequent head losses due to erosion and sediment deposits. Also, the methods used for tunnelling have improved over the years, being able to make smoother tunnels.

Their modernization can bring back the original head and flow capacity. It is evident that for a constant geodetic head, head losses can be decreased by 25 to 40% while power increases by 5% to 10%, which would result in an equivalent gain in generation.

4.7. Efficient use of water resources

A greater percentage of the available water resources will be used when the installation coefficient is modified by installing new turbines or upgrading the existing turbines. If not adequately managed, though, this could also result in more negative effects on the environment (see Fig.12). By increasing the turbine capacity, the hydropower plant can utilize more of the available flow, especially during periods of high flow. This can help offset the potential decrease in water availability due to climate change. The installation coefficient is the ratio of the installed flow to the average annual flow. By adjusting this coefficient, the hydropower plant can control how much of the available flow is used for power generation. For example, during periods of low flow, the coefficient can be reduced to conserve water for ecological purposes.

By implementing these adaptation strategies, hydropower plants can become more resilient to climate change and continue to provide reliable energy. Hydrological drought, as defined by A. F. Van Loon, is a deficiency in the hydrological system characterized by abnormally low flows in rivers, lakes, reservoirs, and groundwater. This type of drought often follows meteorological drought (a prolonged period of below-average precipitation) but can also be influenced by other factors such as increased evapotranspiration or changes in land use.

The flow duration curve (FDC, Figure 12) is a valuable tool for hydrological drought analysis. It plots the percentage of time that a given flow rate is exceeded or equalled. The FDC can be used to estimate the amount of water available for various uses under different drought conditions.

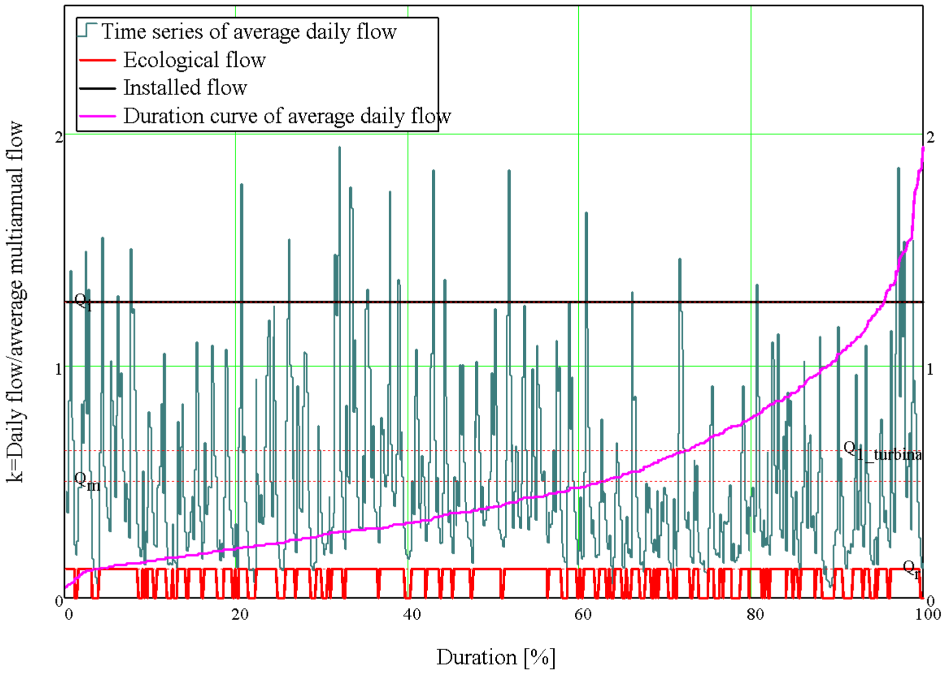

Figure 12. The duration curve of average daily flows.

Hydrological drought analysis, including the use of flow duration curves, is a critical component of climate change adaptation. By understanding the frequency and severity of droughts, we can develop effective strategies to manage water resources, protect communities, and build resilience to future climate challenges [103].

5. Economic analysis and viability

The advantages of investing in the refurbishment and refitment of existing hydropower facilities in Romania are numerous. Such investments would provide low operating and maintenance costs, long life spans (50 to 100 years and more), load flexibility (i.e hydro with reservoir), reliable service, a high energy efficiency rate (payback ratio and conversion process), employment opportunities, revenues to sustain other water uses, and energy independence by exploiting national resources [19]. Also, refitment friendly policies would foster regional development and optimize the power supply of other generating options such as intermittent renewables.

The economic viability of hydropower retrofitting has gained increasing attention in Romania, where much of the hydropower infrastructure dates back several decades. Retrofitting, as opposed to building new hydropower facilities, offers a more cost-effective, faster, and environmentally sustainable alternative. Retrofitting hydropower plants involves the upgrading or modernization of existing facilities to enhance their capacity, efficiency, and environmental performance.

5.1. Hydropower Retrofitting vs. New Hydropower Development: Cost Comparisons

A study comparing the costs of new hydropower projects to retrofitting existing plants has demonstrated that retrofitting can be up to 40% less expensive, (considering the same energy production) depending on site conditions and project scale [21]. The lower costs are attributed to the reduced need for civil engineering works and lower permitting challenges. This is particularly relevant in Romania, where the potential for retrofitting existing plants outweighs the limited availability of new sites for significant hydropower development. Retrofitting presents a solution for upgrading aging hydropower infrastructure, meeting the country's renewable energy goals at a fraction of the cost and with fewer environmental impacts. Additionally, retrofitting projects can proceed more quicker since they typically bypass lengthy permitting processes and avoid extensive environmental impact assessments that are mandatory for new constructions.

Retrofitting existing hydropower plants is more affordable than building new ones for several key reasons. Existing dams, reservoirs, and much of the civil infrastructure can be repurposed, minimizing the upfront capital costs typically associated with hydropower development. This is especially relevant in Romania, where many hydropower plants were constructed during the Communist era and remain in operation today. Instead of constructing entirely new facilities, which would require land acquisition, environmental impact assessments, and construction from scratch, retrofitting focuses on modernizing turbines, generators, and control systems. These upgrades enhance energy output and efficiency without the need for significant new construction. Building a new hydropower plant involves several costly phases: civil engineering (construction of dams, tunnels, and reservoirs), installation of new turbines and generators, and addressing environmental and social impacts. Retrofitting, by contrast, requires only the modernization of existing infrastructure, including the replacement or refurbishment of turbines, generators, control systems, and electrical components. Hydropower retrofitting offers significant economic advantages over the construction of new hydropower plants [20]. The primary economic benefit arises from the use of existing infrastructure. Retrofitting typically involves upgrading turbines, generators, or control systems within the existing dam structure, eliminating the need for extensive land acquisition, site preparation, and civil construction—costly components of new hydropower projects. In contrast, building a new hydropower facility often requires large initial capital investments, including environmental impact assessments, permits, and the construction of entirely new reservoirs, which involve substantial financial and time-related expenditures.

The reduction in costs also stems from technological advancements. Upgraded turbines and control systems significantly increase the efficiency of existing plants, allowing them to generate more electricity from the same water flow [2]. Moreover, retrofitting helps extend the lifespan of older plants by enhancing their reliability and minimizing operational and maintenance costs. A well-executed retrofitting project can generate high returns on investment by maximizing the use of water resources and improving overall system performance.

5.2. Methods of Economic Analysis in Hydropower Retrofitting

Economic analysis is essential to evaluate the viability of retrofitting projects [22]. Several methods are used in such assessments, each focusing on different financial aspects. These include cost-benefit analysis (CBA), internal rate of return (IRR), and net present value (NPV). For the purposes of this chapter, we apply these methods to the retrofitting project of the Lotru-Ciunget hydropower plant to illustrate their effectiveness in determining economic viability.

5.3. Cost-Benefit Analysis (CBA)

Cost-benefit analysis is a systematic approach to comparing the costs and benefits of a project over time. In hydropower retrofitting, the primary costs include the capital expenditures (CAPEX) of replacing turbines, generators, and other essential equipment, as well as the operational expenditures (OPEX) of maintaining and running the plant. Benefits, on the other hand, include increased energy output, improved efficiency, and the extension of the plant's operational life, benefits which heavily outweigh costs when discussing about a country’s energy potential [19].

Unfortunately, there is no possible way to quantify the biodiversity loss, water quality diminishment, erosion and the many other issues associated with building a new hydropower plant. The only thing quantifiable is the comparison of consequences on the environment, water and landscape between building a new facility and retrofitting/refurbishing an existing one, the consequences being much worse in the former case.

5.4 Economic Metrics and Methods for Hydropower Retrofitting

Economic feasibility is commonly assessed through various financial metrics. Two of the most widely used are Net Present Value (NPV) and Internal Rate of Return (IRR). These metrics provide insights into whether a project is financially viable and how it compares to alternative investments.

The NPV method calculates the present value of future cash flows from a project, discounted to reflect the time value of money. The formula is:

$$NPV = \sum_{t=1}^{T} \frac{R_t}{(1+r)^t} - C_0$$

Where:

- $\left(R_t\right)$, represents the net cash inflow in year (t);
- (r), is the discount rate;
- (C_0), is the initial investment cost;
- (T), is the project lifespan.

A positive NPV indicates that the project is expected to generate more value than it costs, making it a sound investment.

The IRR is the discount rate that sets the NPV to zero. It indicates the annualized return on investment. If the IRR exceeds the project's cost of capital, the investment is considered worthwhile. The formula is:

$$0 = \sum_{t=1}^{T} \left(\frac{R_t}{(1+IRR)^t}\right) - C_0$$

Both NPV and IRR are useful in evaluating the viability of hydropower retrofitting projects.

5.5. Economic Analysis of the Vidraru and Lotru-Ciunget Hydropower Plants

The Vidraru and Lotru-Ciunget Hydropower Plants were the perfect candidates for our analysis because of their scale, production and the fact that the authorities already accepted the fact that refurbishing and retrofitting is needed.

5.5.1. Vidraru Hydropower Plant

The Vidraru Hydropower Plant, built in the 1960s, has been a key component of Romania's hydropower infrastructure for decades. By the late 2010s, the plant required modernization to maintain its operational efficiency and extend its lifespan. In 2018, a major modernization project was undertaken at Vidraru, involving the modernization of turbines, generators, and control systems. This project is in its early stages of contracting.

The total investment in the Vidraru retrofit was initially approximated at €100 million [23], unfortunately the true cost was around €189 million [24]. The upgrades resulted in a 20% increase in energy generation capacity, from 220 MW to 264 MW. The retrofitting also extended the plant’s operational life by another 40 years, with reduced maintenance costs due to the installation of more reliable equipment.

We now perform an economic analysis of the Vidraru retrofit project using the NPV method. The plant generates an additional 44 MW of capacity, which translates into approximately 80 GWh of additional electricity per year. Assuming an average electricity price of €100 per MWh, the additional revenue from the retrofit is €8 million per year. The operation and maintenance costs are estimated at €500,000 annually, and the discount rate used is 6%.

$$NPV = \sum_{t=1}^{40} \left(\frac{(8,000,000-500,000)}{(1+0.06)^t}\right) - 189,000,000$$

Over the course of the project's 40-year expected lifespan, the Vidraru retrofit demonstrates a subpar return on investment. The IRR, calculated using the same cash flow data, is approximately 3%, which is below the 6% cost of capital, making the project an underperforming endeavor, but if it would have cost only €100 million the results would be completely different. Although the cost were nearly double the investment can still be regarded as almost even (not profitable, but also not a significant loss), also the Vidraru retrofit can be considered a strategic move, as its energy production is vital. The modernization also extended the operational life of the plant by 40 years, reducing future costs for maintenance and repairs.

5.5.2. Lotru-Ciunget Hydropower Plant

The Lotru-Ciunget Hydropower Plant, one of the largest in Romania, was built in the 1970s and underwent a major retrofitting project in 2010. The retrofit aimed to enhance the plant's efficiency, improve environmental performance, and extend its operational lifespan. With a generation capacity of 510 MW, Lotru-Ciunget is a vital source of renewable energy in Romania.

In the case of the Lotru-Ciunget hydropower plant, the CBA reveals significant economic advantages. Before the retrofit, the plant had a capacity of 510 MW, generating an average of 1,000 GWh annually. The retrofit involved modernizing the turbines and generators, leading to an estimated 10% increase in energy output without expanding the dam or reservoir. The total cost of the retrofit was approximately €88 million [25].

The benefits of this retrofit are twofold. First, the increase in energy output generates additional revenue. Assuming an average electricity price of €100 per MWh, the additional 100 GWh of electricity produced annually represents an extra €1 million in revenue per year. Second, the retrofit extended the operational life of the plant by an estimated 30 years, providing a long-term benefit in terms of stable, renewable energy generation. The operational and maintenance costs for the upgraded plant are estimated at €700,000 annually. Applying a discount rate of 6%, we can calculate the NPV of the Lotru-Ciunget retrofit as:

$$NPV = \sum_{t=1}^{30} \frac{(11{,}000{,}000 - 700{,}000)}{(1+0.06)^t} - 88{,}000{,}000$$

The NPV is significantly positive, reflecting the strong financial performance of the project. The IRR, calculated iteratively, is approximately 11%, which further demonstrates that the retrofit was a sound financial decision. The upgrades have extended the plant's operational life by 40 years, reduced maintenance costs, and increased energy output, providing long-term value.

5.6. The Broader Economic Impact of Hydropower Retrofitting

Beyond the individual project level, hydropower retrofitting has broader economic implications for Romania's energy sector. By modernizing existing plants, the country can reduce its reliance on imported energy, stabilize electricity prices, and enhance grid resilience. In addition to these quantitative metrics, qualitative factors also play a role in the economic assessment of hydropower retrofitting. Environmental benefits, such as reduced carbon emissions and improved water management, can translate into economic value, especially in markets with carbon pricing mechanisms or where companies can earn renewable energy credits. Furthermore, retrofitting projects tend to have shorter implementation timelines compared to new builds, reducing the risk of regulatory changes or market shifts that could impact project economics.

This is particularly important as Romania seeks to meet its commitments under the European Union's Green Deal, which calls for a transition to carbon-neutral energy systems by 2050, and which states that renewable energy in gross energy consumption must increase to 36% by 2030. Hydropower, being one of the most mature and reliable forms of renewable energy, plays a critical role in this transition [26].

Moreover, retrofitting projects create jobs and stimulate local economies. From equipment manufacturing to construction and engineering services, these projects have a multiplier effect on local and regional economies, supporting both short-term employment during the upgrade process and long-term jobs in plant operation and maintenance.

The economic analysis of the Vidraru and Lotru-Ciunget Hydropower Plants demonstrates that retrofitting is a cost-effective alternative to building new hydropower facilities. Both projects achieved substantial improvements in efficiency and capacity at a fraction of the cost of new construction, delivering positive NPVs and strong IRRs.

In Romania, where the potential for large-scale new hydropower development is limited, retrofitting existing plants like Vidraru and Lotru-Ciunget provides a pathway for meeting renewable energy targets while minimizing environmental and financial costs.

6. Environmental impact and Climate change

While hydropower has been scrutinized for its environmental impact, there is no doubt that it is cleaner than fossil fuel burning. The demolition or decommissioning of large existing hydropower facilities would also have a harsh impact on the environment, so the refitment or refurbishment of such facilities would be the best choice with regard to the environment. Some advantages of this type of energy generation include its production of limited atmospheric pollutants caused by equipment transport, no consumption or pollution of water used for electricity, zero waste production, avoidance of depleting non-renewable resources, minimal greenhouse gas emissions compared to other large-scale options, the potential to recreate new freshwater ecosystems with increased productivity, enhanced knowledge and management of valued species, and increased attention to existing environmental issues in the affected area. However, when existing hydropower plants are no longer functional and retrofitting is not an economically efficient solution, their decommissioning should align with broader environmental restoration initiatives. The **EU Nature Restoration Law**, for example, aims to restore 25,000 km of rivers across Europe, emphasizing the removal of obsolete dams and barriers to re-establish free-flowing rivers. Programs such as the **Open Rivers program** highlight the ecological and societal benefits of dam removal, including habitat restoration, improved biodiversity, and the reestablishment of sediment transport. A relevant study, *Dam Removal: A European Perspective*, provides compelling evidence of the positive impacts of such measures, noting that restoring natural river dynamics contributes significantly to ecosystem health and resilience. Integrating these trends as solutions where hydropower plants are beyond retrofitting viability ensures a balanced approach that prioritizes both renewable energy and environmental restoration [27]

The disadvantages include the flooding of terrestrial habitats, modification of hydrological and aquatic regimes, lower water quality discharged from dams, greenhouse gas emissions from reservoirs, barriers to fish migration and potential fish entrainment, the need to monitor and manage sediment composition and transport to limit reservoir sedimentation, and the introduction of invasive species [28].

Important conclusions capturing these concerns were that dams have made an important and significant contribution to human development, and the benefits derived from them have been considerable. In too many cases, an unacceptable and often unnecessary price has been paid to secure those benefits, especially in social and environmental terms, by communities downstream, by taxpayers, and by the natural environment [29, 30].

Hydropower has long been seen as one of the most reliable and environmentally friendly forms of energy generation. It offers a sustainable way to meet rising energy demands while producing far fewer carbon emissions compared to fossil fuels [31]. However, even though it is generally cleaner, hydropower is not without its environmental challenges. Retrofitting Romania's aging hydropower plants to enhance energy efficiency and integrate with modern grids brings forth critical questions about environmental impact and the broader implications of climate change.

As Romania upgrades its hydropower infrastructure, it must navigate a delicate balance between harnessing renewable energy and mitigating environmental risks. The impact of hydropower retrofitting on local ecosystems, water quality, biodiversity, and broader climate change dynamics is complex and multifaceted. In this chapter, we will explore the key environmental concerns associated with hydropower retrofitting in

Romania, analyze how climate change may influence hydropower potential, and examine the policies and strategies that can ensure the modernization process aligns with sustainable development goals. The "State of Climate - Romania 2024" report emphasizes Romania's climate challenges, particularly the intensification of heatwaves, droughts, and extreme weather events. Key findings highlight that Romania's average temperature rose by 1.48°C above preindustrial levels in 2023, with heatwaves lasting 10–15 days longer in most regions, and up to 25–30 days longer in the southwest and eastern areas. The impact of climate change on Romania's water resources underscores the potential role of hydropower as a climate adaptation strategy. Increasing reliance on hydropower, especially through retrofitting existing facilities, could enhance water management, reduce emissions, and support a more resilient energy infrastructure amid changing precipitation patterns and rising demand. [32].

6.1. Hydrological and Ecosystem Impacts

Hydropower's reliance on natural watercourses inherently affects the hydrological and ecological systems surrounding its installations [33]. In Romania, the country's rich water resources—including major rivers such as the Danube and its tributaries—have provided fertile ground for hydropower development. However, the construction and operation of hydropower plants have historically altered water flows, impacting both aquatic and terrestrial ecosystems. Retrofitting older hydropower plants poses an opportunity to address some of these concerns, but it also introduces new challenges.

One of the primary environmental impacts of hydropower is the alteration of river flow regimes. Dams and reservoirs change the natural seasonal variation in water levels, which can disrupt the migration patterns of fish and other aquatic species [33]. This is particularly true in run-of-river projects where the continuous diversion of water to turbines reduces downstream flows, potentially affecting the biological health of rivers [34]. Fish species, such as the endangered sturgeon in the Danube, have already seen declines in population due to barriers to migration. In Romania's hydropower retrofitting projects, addressing fish migration is crucial. Newer technologies such as fish ladders and bypass systems are designed to allow aquatic species to traverse dams more easily, but these solutions must be carefully tailored to local conditions to be effective.

Beyond direct impacts on aquatic species, the modification of river flows has a broader effect on the entire riverine ecosystem [35]. Wetlands, which often rely on regular flooding cycles, can shrink or disappear when water levels are artificially controlled. In Romania, wetlands are a vital part of the ecosystem, providing habitats for various species of birds, mammals, and amphibians. They also play a crucial role in carbon sequestration and water purification. Therefore, retrofitting projects should incorporate water management strategies that mimic natural flow patterns, ensuring that downstream ecosystems remain resilient and functional.

Sediment management is another important consideration in the environmental impact of hydropower retrofitting [36]. Dams and reservoirs often trap sediment that would otherwise flow downstream, affecting negatively river morphology and delta formations. This issue is particularly pronounced in Romania's Danube Delta, one of Europe's most biodiverse regions and a UNESCO World Heritage Site [37]. The buildup of sediment in reservoirs reduces their storage capacity and can degrade water quality. Sediment starvation downstream can lead to the erosion of riverbanks and the loss of fertile land in agricultural areas. To mitigate these impacts, retrofitting efforts should include sediment bypass systems, dredging strategies that maintain sediment transport to downstream ecosystems and limitation strategies to decrease the negative effect on groundwater levels.

Water quality can also be impacted by hydropower operations [38], especially in reservoirs where stagnant water conditions can lead to the growth of harmful algal blooms and reduced oxygen levels [39]. These conditions can negatively affect both aquatic life and human water uses. Retrofitting Romania's hydropower plants offers an opportunity to improve water quality through better reservoir management practices. Installing aeration systems and optimizing water release schedules can help maintain healthy oxygen levels in water bodies [38, 39].

6.2. Climate Change and Water Resources

Climate change presents a significant challenge to the long-term viability of hydropower in Romania. Changes in precipitation patterns, rising temperatures, and shifting hydrological cycles are already being observed across Europe, and Romania is no exception [40,41]. The country's hydropower potential is closely tied to its water resources, which are vulnerable to climate-driven variability [40]. As the climate changes, Romania could face both opportunities and risks in the operation of its hydropower plants. Drought has worsened in recent years, severely impacting agriculture and increasing the arid land area. The report foresees more frequent and intense storms, with urban heat islands exacerbating temperatures in cities, affecting nearly half the urban population by 2040 [31].

Figure 12 shows: a) Time evolution and b), c), d) and e) - changes in the annual average temperature. In b) and c) the maps show temperature changes for the period 2031-2050, and in d) and e) the maps show temperature changes for the period 2071-2100. The maps on the left show the changes resulting from the medium emissions scenario (RCP4.5), while the maps on the right show the changes resulting from the high emissions scenario (RCP8.5). In b), c), d) and e) the changes are reported for the period 1971-2000. The shaded areas indicate statistically significant trends (99% significance level).

Figure 14 highlights the annual fluctuations in annual precipitation amounts in Romania from 1971 to 2100, for the RCP scenario with medium emissions (RCP4.5, green line) and the RCP scenario with high emissions (RCP8.5, blue line).

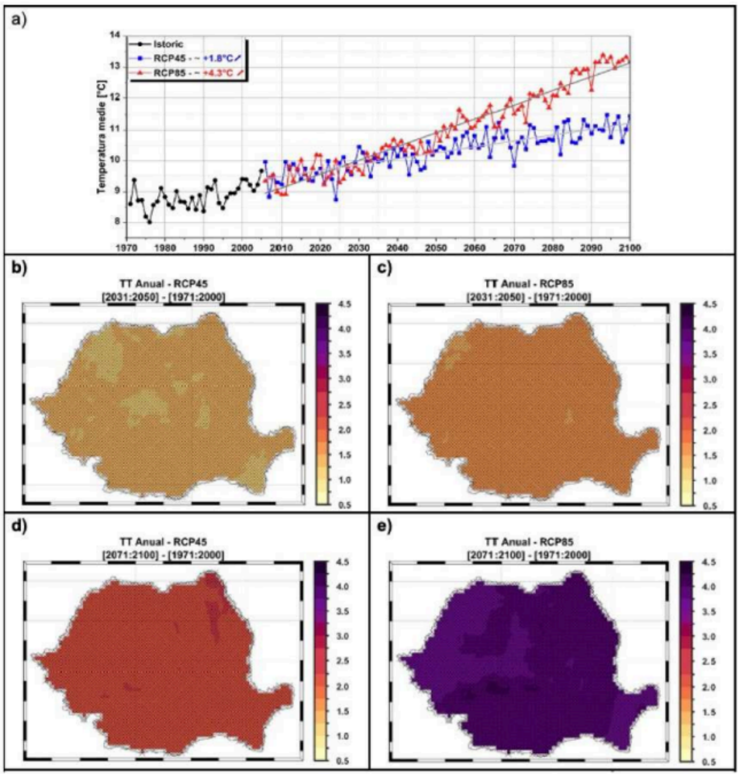

Figure 13. Temperature changes [42].

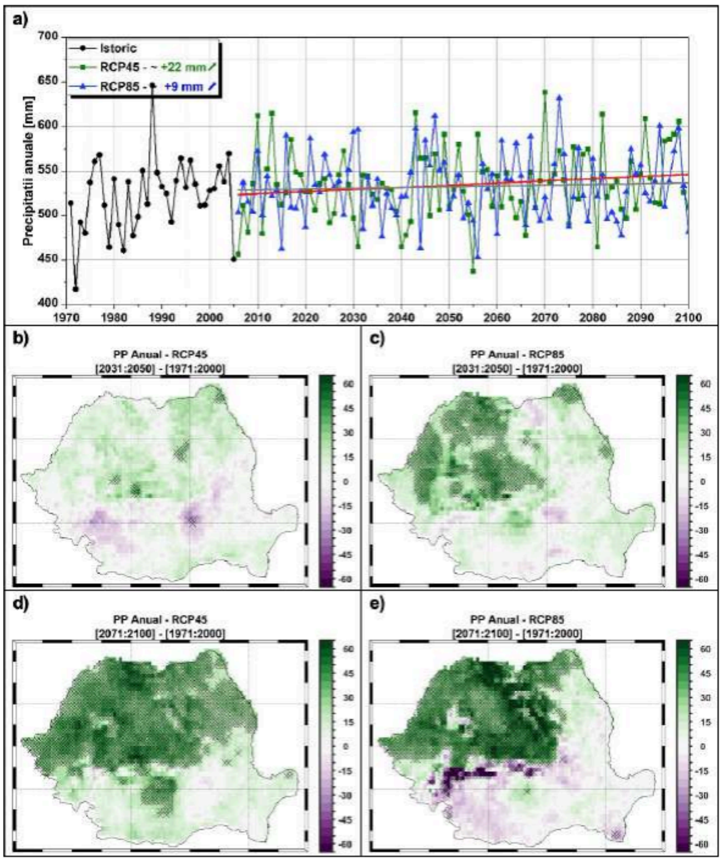

Figure 14. Annual fluctuations in annual precipitation amounts in Romania [42]

One of the key impacts of climate change on hydropower is the alteration of water availability. Hydropower relies on consistent and predictable water flows, which are influenced by precipitation, snowmelt, and river runoff. In Romania, climate models predict that southern regions may experience more frequent droughts, while northern areas could see an increase in intense rainfall events. This variability poses a challenge for hydropower plants, particularly those located in river basins where water flows are already highly seasonal. Drought conditions can reduce water availability, limiting the capacity of hydropower plants to generate electricity during critical periods [42]. On the other hand, increased rainfall could lead to higher water flows, providing more opportunities for power generation but also increasing the risk of flooding and reservoir overflow [43].

Retrofitting Romania's hydropower plants to account for these changing conditions will require careful hydrological planning. Modernizing infrastructure to handle a wider range of flow conditions will be essential. Variable speed turbines, for example, can adjust their operation to optimize energy production under both high and low flow scenarios [44]. Additionally, advanced forecasting systems that integrate climate data can help operators better anticipate water availability and manage hydropower assets more effectively. By incorporating climate resilience into retrofitting strategies, Romania can ensure that its hydropower sector remains a reliable source of renewable energy in the face of growing climatic uncertainty.

The changes in snowpack accumulation are also factors that could affect Romania's hydropower potential. While the country does not rely heavily on snowmelt for hydropower, changes in the broader European hydrological system, including the Carpathian Mountain range, could influence water flows into major river systems like the Danube. Warmer winters may result in reduced snowpack and earlier snowmelt, leading to lower water availability during the summer months when electricity demand is highest [45]. Retrofitting strategies should therefore consider the potential for more variable water flows and incorporate adaptive measures to deal with these shifts.

Climate change also raises concerns about the long-term sustainability of Romania's water resources [46]. Hydropower plants can place significant demands on local water supplies, especially during dry periods when competition for water between energy production, agriculture, and municipal use becomes more pronounced. In regions where water scarcity is becoming more acute due to climate change, this could lead to conflicts over resource allocation. To mitigate these risks, Romania must adopt an integrated water management approach that balances the needs of hydropower with other critical water uses. This approach should prioritize water conservation, efficient use, and the protection of vulnerable ecosystems.

6.3. Carbon Emissions and Greenhouse Gas Considerations

The energy sector is currently the largest contributor to global greenhouse gas (GHG) emissions and is facing growing pressure to reduce its carbon footprint. Hydropower's role in mitigating climate change is multifaceted, including its contributions, uncertainties, risks, and potential opportunities [47]. As the energy sector accounts for around 35% of global emissions, efforts to mitigate climate change will focus largely on transforming this sector. Reducing the carbon footprint of electricity production can be achieved by increasing system efficiency and expanding the use of renewable energy sources, thus reducing reliance on fossil fuels [48, 49, 50, 51].

Hydropower plays a crucial role in two ways: it acts as a renewable energy source that can replace fossil fuels in power generation, and it serves as an energy storage technology that enables greater integration of intermittent renewable sources like wind and solar power. In 2014, hydropower led global renewable energy technologies, with an installed capacity of 1,036 GW and a total generation of 3,900 TWh/year [52]. It is widely regarded as a clean, renewable, and low-carbon energy technology, instrumental in offsetting fossil fuel use. Hydropower's emissions are relatively low, averaging 28 g CO2e/kWh, far below other generation technologies, such as gas-fired generation (490 g CO2e/kWh) and coal-fired generation (820 g CO2e/kWh) [47, 49].

To address the uncertainties surrounding the greenhouse gas emissions of reservoirs, the UNFCCC developed a provisional method based on the reservoir area and the capacity of the hydropower plant, known as the 'power density' approach. This categorizes hydropower projects and assigns an emissions profile to each category under the Clean Development Mechanism (CDM). While this methodology offers a general guide for estimating emissions, it is recognized that the approach might overestimate hydropower's emissions compared to the overall emissions of the power grid it supports [48, 51].

In addition to being the largest source of renewable electricity, hydropower's unique ability to store energy makes it essential for integrating variable renewable energy sources like wind and solar. Hydropower reservoirs are already vital in balancing energy supply and demand, providing 99% of the world's electricity storage capacity [52]. As renewable energy sources, particularly wind and solar, continue to expand, the need for energy storage will become even more crucial. Hydropower can compensate for intermittent renewable energy by releasing stored water when solar or wind output is insufficient and storing energy during periods of excess renewable generation. Moreover, hydropower contributes to grid stability by maintaining voltage and frequency levels, a role that will grow as the transition to renewable energy accelerates. The energy sector is currently the largest contributor to global greenhouse gas (GHG) emissions and is facing growing pressure to reduce its carbon footprint. Hydropower's role in mitigating climate change is multifaceted, including its contributions, uncertainties, risks, and potential opportunities [51]. As the electricity and transformation sector accounts for around 35% of global emissions, efforts to mitigate climate change will focus largely on transforming this sector. Reducing the carbon footprint of electricity production can be achieved by increasing system efficiency and expanding the use of renewable energy sources, thus reducing reliance on fossil fuels [49, 50, 51].

The construction phase of hydropower retrofitting projects can result in significant GHG emissions [53], particularly if it involves large-scale concrete works, transportation of materials, and heavy machinery use. Concrete production is energy-intensive and contributes substantially to global carbon emissions. Therefore, retrofitting projects should prioritize the use of low-carbon construction materials and adopt energy-efficient practices wherever possible. Additionally, lifecycle assessments should be conducted to evaluate the total carbon impact of retrofitting, ensuring that the long-term benefits outweigh the short-term emissions costs.

Methane emissions from reservoirs are another environmental concern associated with hydropower. Reservoirs, particularly in tropical and temperate climates, can produce methane through the decomposition of organic matter that accumulates at the bottom of the water body [54,55]. This methane is eventually released into the atmosphere, contributing to global warming. While Romania's temperate climate may result in lower methane emissions compared to tropical regions, some reservoirs could still produce significant amounts of methane, particularly if organic material from agricultural runoff or forest debris accumulates. Retrofitting projects should therefore include strategies to minimize methane emissions, such as enhancing water flow circulation in reservoirs and improving land management practices in the surrounding catchment areas to reduce organic matter inflow [55].

By upgrading existing plants rather than constructing new dams, Romania can avoid some of the environmental impacts associated with new hydropower development, such as deforestation and the loss of biodiversity. Retrofitting existing infrastructure also reduces the need for additional land use, helping to preserve natural habitats. From a climate change perspective, this is a significant advantage, as it limits the disruption of carbon sinks like forests and wetlands, which play a critical role in mitigating global warming.

6.4. Policy Framework and Environmental Protection

Romania's approach to hydropower retrofitting must align with both national and European Union environmental policies. The European Green Deal and the EU's commitment to climate neutrality by 2050 place a strong emphasis on reducing emissions, protecting biodiversity, and promoting sustainable resource management. Romania, as an EU member state, is obligated to comply with directives such as the Water Framework Directive (WFD) and the Habitats Directive, both of which have direct implications for hydropower operations [56, 57].

The WFD mandates that all European water bodies achieve "good ecological status," which includes maintaining healthy aquatic ecosystems and ensuring that human activities, such as hydropower generation, do not degrade water quality. Retrofitting Romania's hydropower plants must therefore be undertaken with careful consideration of ecological impacts. Environmental impact assessments (EIAs) will play a key role in identifying potential risks and ensuring that mitigation measures are implemented. These assessments should consider factors such as changes in river flow regimes, impacts on biodiversity, and potential risks to water quality.

The Habitats Directive is another important piece of legislation that protects species and habitats of European importance [58]. Many of Romania's rivers and wetlands are home to endangered species, such as the Danube sturgeon, which are highly sensitive to changes in water conditions. Retrofitting projects must ensure that they do not harm protected habitats or species, and where necessary, compensatory measures should be taken to enhance biodiversity. For example, the construction of artificial spawning grounds or the restoration of degraded wetlands could help offset some of the negative impacts of hydropower operations.

Romania's national environmental policies also emphasize the need for sustainable hydropower development. The National Energy Strategy outlines the importance of modernizing the country's hydropower sector while minimizing environmental impacts. Retrofitting projects will need to adhere to these guidelines, incorporating best practices for environmental protection and ensuring that Romania's hydropower sector continues to contribute to the country's climate goals without compromising ecological integrity.

6.5. Environmental conclusions

The environmental impact of hydropower retrofitting in Romania is complex and multifaceted, involving both challenges and opportunities. While hydropower is a key component of Romania's renewable energy portfolio, its impact on ecosystems, water resources, and biodiversity cannot be overlooked. Retrofitting offers a chance to mitigate some of the environmental harm caused by older hydropower plants, but it also introduces new challenges, particularly in the context of climate change.

As Romania moves forward with its hydropower modernization efforts, careful consideration must be given to the protection of aquatic ecosystems, sustainable water management, and the reduction of greenhouse gas emissions. By aligning retrofitting projects with European and national environmental policies, Romania can ensure that its hydropower sector contributes to the country's climate resilience and sustainability goals, while also safeguarding its rich natural heritage for future generations.

7. Stakeholder engagement

In the context of hydropower retrofitting in Romania, stakeholder engagement emerges as a pivotal aspect that underpins both the success and sustainability of hydropower initiatives [59]. Engaging a diverse range of stakeholders not only enhances the robustness of the retrofitting process but also ensures that the interests and concerns of all parties are adequately represented and addressed. The complexity of the hydropower landscape in Romania, characterized by a mixture of environmental, social, economic, and technological dimensions, necessitates a comprehensive engagement strategy. As Romania seeks to optimize its hydropower resources while balancing environmental and social considerations, a well-structured and comprehensive stakeholder engagement strategy becomes essential.

Effective stakeholder engagement begins with identifying the key stakeholders involved in the hydropower sector. These include government bodies at various levels, local communities, protected areas administrators, environmental organizations, fishermen associations, hydropower operators, researchers, and industry experts. Each stakeholder group brings its perspectives, interests, and levels of influence to the table [60]. For instance, government agencies are often tasked with regulatory oversight and policy formulation, while local communities may prioritize the socio-economic impacts of retrofitting projects, such as job creation and environmental preservation. This collaborative approach is particularly important in a sector like hydropower, where projects can have profound implications for local ecosystems and communities.

Government agencies at local, regional, and national levels play a critical role in regulating hydropower projects. They are responsible for establishing policies, issuing permits, and ensuring compliance with environmental laws. Engaging these entities early is essential for understanding regulatory requirements and aligning project goals with national energy policies.

Local communities are often directly impacted by hydropower projects [61]. Their insights into local needs, traditions, and socio-economic conditions are invaluable. Engagement with these groups should prioritize understanding their concerns, aspirations, and potential benefits they expect from retrofitting projects. Community involvement can also enhance project acceptance and facilitate smoother implementation [60].

Environmental NGOs and advocacy groups are crucial stakeholders in the hydropower sector. They often possess expertise in ecological conservation and can provide critical insights into the potential environmental impacts of retrofitting initiatives. Early engagement with these organizations is vital for developing effective mitigation strategies and ensuring that ecological considerations are prioritized.

Hydropower operators are key stakeholders who bring technical expertise and operational knowledge to the table. Their involvement is essential for understanding the practical implications of retrofitting projects, including technical feasibility, cost considerations, and potential impacts on energy production. Collaboration with operators can lead to innovative solutions that optimize both energy efficiency and environmental performance [62].

Academic institutions and researchers can provide valuable data, analysis, and scientific insights that inform decision-making processes. Engaging researchers early in the project can help identify best practices, evaluate potential impacts, and enhance the overall quality of the retrofitting efforts. Collaborative research initiatives can also foster knowledge transfer and capacity building among stakeholders.

A foundational element of stakeholder engagement is establishing clear communication channels. Transparent communication fosters trust and encourages active participation, allowing stakeholders to voice their concerns and contribute to decision-making processes. In the context of hydropower retrofitting, this can involve public meetings, workshops, and informational campaigns designed to disseminate knowledge about the retrofitting process, its potential benefits, and its challenges. Engaging stakeholders through multiple platforms ensures that diverse voices are heard, particularly those of marginalized groups who may otherwise be overlooked [59].

Furthermore, stakeholder engagement is not a one-time event but a continuous process that evolves throughout the retrofitting lifecycle. Initial engagement efforts should focus on raising awareness and generating interest in the retrofitting potential of existing hydropower plants. As the project progresses, stakeholders should be kept informed about developments, and their feedback should be solicited to refine and adapt strategies [63]. This iterative approach allows for the incorporation of local knowledge and expertise, which can significantly enhance the effectiveness of retrofitting projects.

An essential aspect of stakeholder engagement in the hydropower sector is addressing environmental and social concerns. The modification of existing hydropower infrastructure can have profound implications for local ecosystems and communities. Therefore, it is crucial to engage environmental organizations and advocacy groups early in the process. These stakeholders can provide valuable insights into the potential ecological impacts of retrofitting initiatives, including changes to aquatic habitats, fish migration patterns, and water quality. Collaborating with these groups not only helps in identifying potential risks but also in developing mitigation strategies that can alleviate negative outcomes.

The economic implications of hydropower retrofitting also warrant careful consideration. Engaging with local communities, particularly those that are directly affected by hydropower operations, can yield critical information regarding the socio-economic dynamics at play. It is essential to understand how retrofitting projects can contribute to local economies through job creation, increased energy efficiency, and potential revenue from improved energy production. Additionally, local stakeholders can offer insights into cultural values and historical ties to the land and water resources that might inform the retrofitting process and its community acceptance.

To facilitate effective stakeholder engagement, it is also important to recognize and address potential conflicts of interest in a transparent manner [64]. For example, hydropower operators may prioritize maximizing energy output and operational efficiency, while environmental groups may advocate for stricter ecological protections. Navigating these competing interests requires skilled facilitation and a commitment to finding common ground. Mediated discussions can provide a platform for stakeholders to express their views openly and seek collaborative solutions that balance energy needs with environmental stewardship [59].

Stakeholder engagement is a critical element of hydropower retrofitting in Romania. By fostering open communication, addressing diverse interests, and incorporating local knowledge, the engagement process can significantly contribute to the development of sustainable and equitable retrofitting strategies. The complexities inherent in the hydropower sector necessitate a collaborative approach that acknowledges and respects the voices of all stakeholders while harnessing their collective insights. As Romania moves forward with its retrofitting hydropower initiatives, a commitment to inclusive stakeholder engagement will be essential in navigating the challenges and opportunities that lie ahead. Through thoughtful and consistent engagement, the potential for hydropower as a clean and renewable energy source can be realized, ensuring that both environmental and social well-being are preserved in the pursuit of energy sustainability.

8. Integration with Romania's Power Grid

Effective grid integration is essential for maximizing the benefits of retrofitting Romania's hydropower plants. Hydropower is inherently flexible in terms of electricity generation, making it a valuable asset for balancing supply and demand on the grid. However, Romania's power grid is facing increased pressure from the rising share of variable renewable energy sources such as wind and solar. These sources generate electricity intermittently, leading to potential mismatches between generation and demand. Hydropower retrofitting, particularly through pumped-storage solutions, can play a pivotal role in addressing this challenge by providing reliable dispatchable power.

The modernization of hydropower plants should be designed with grid flexibility in mind. This means that retrofitted plants must be able to rapidly adjust their output in response to grid fluctuations. One key solution involves the incorporation of automated grid balancing systems that can control hydropower plants in real time. By integrating smart grid technologies, Romania’s hydropower plants could become a central part of the country's energy management strategy, automatically increasing or decreasing generation based on grid needs. For example, during periods of low renewable energy generation, hydropower plants could quickly ramp up their output to compensate for the shortfall. Conversely, when wind and solar generation are high, hydropower plants can reduce output or even absorb excess energy through pumped storage.

The transition to a smarter, more flexible grid also requires investments in grid infrastructure. Romania will need to enhance its transmission and distribution networks to accommodate the dynamic operation of retrofitted hydropower plants. This involves upgrading substations, installing advanced transformers, and improving interconnections between hydropower plants and other renewable energy sources. Moreover, Romania's grid will need to be upgraded to better accommodate cross-border electricity flows, allowing it to participate more fully in the European internal energy market. The European Union has set ambitious targets for cross-border interconnections under the European Green Deal, which Romania will need to meet to fully leverage its hydropower potential.

9. Discussions

The Integrated National Plan (PNI) proposes the development of the new solar energy and microhydro energy capacities provided for in the Decarbonization Plan will contribute to achieving the SRE-E target and will ensure the diversification of energy sources, but the National Strategy for Water Management Romania (SNGA) quotes a truncated part of Romania's Energy Strategy 2020-2030, with the perspective of the year 2050, the original text being "In accordance with environmental policies, reducing or eliminating the negative impact on the ecological state of running waters produced by microhydropower plants with derivation plants, Romania must unlock such started projects and start new projects." [15].

The SNGA vaguely mentions the need to achieve the financing of investment objectives for hydropower facilities and hydrotechnical and energy complexes without citing the Energy Strategy of Romania 2020-2030, with the perspective of the year 2050 (proposal), namely "Realization of some strategic projects of Hidroelectrica (modernizations, re-technologies, i.e. the completion of the main investment objectives under execution), to which are added offshore investments and pumped storage plants, will also contribute to the replacement of polluting capacities and the flexibility of the national energy system."

In the text of the proposal regarding Romania's Energy Strategy 2020-2030, with the perspective of 2050, the reference to the ecological flow has disappeared "In this sense, for large hydropower facilities, the transition will be carried out gradually until 2030, through three stages of adjustment, for to reach compliance with average European standards in the field, and for small-scale hydropower installations, compliance with average European standards will be achieved by 2025", because the regulation of the method of determining and calculating the ecological flow, HG 148/ 2020 has an annex with disproportionate costs that thus exempts some hydropower capacities (including microhydropower), and in particular all the hydropower capacities of S.P.E.E.H. HIDROELECTRICA S.A., and large hydroelectric power stations and small hydropower plants.

10. Conclusions and future directions

The Romanian authorities show omissions in that they do not pay enough attention to optimizing the operation of hydroelectric plants, thus ignoring a significant potential for increasing energy efficiency and limiting themselves to an outdated approach regarding the development of the hydropower sector, focusing on the development of new capacities hydropower plants with an impact on the environment and an inefficient use of water resources. It ignores the potential to increase the efficiency and energy production of already existing hydroelectric plants resulting in missing out on a significant potential to increase the production of renewable energy, without requiring the construction of new dams that have the effect of increasing greenhouse gas emissions greenhouse for the whole life cycle.

Detailed studies are needed to identify the potential for increasing the energy efficiency of each individual hydroelectric plant and to develop clear and concrete plans for the modernization of existing hydroelectric plants, including the establishment of precise objectives and a timetable for implementation. This can be done by identifying appropriate sources of funding, both national and European, to support investments in modernization, an example would be the use of the water tax for hydropower uses and government transparency about its use in promoting increased energy efficiency of hydroelectric plants.

While the technical and environmental challenges of retrofitting have been extensively discussed, it is equally important to consider the steps that will follow the completion of these upgrades. Hydropower retrofitting is not a one-time intervention; rather, it is part of a broader process that involves ongoing assessments, further technological improvements, and adaptive strategies in response to evolving energy demands and environmental changes. One of the key areas for follow-up after the retrofitting process is the monitoring of plant performance and environmental impact. Hydropower plants are dynamic systems that interact with their surroundings in complex ways, and retrofitting them introduces new variables into these interactions. After retrofitting, Romania must ensure that the upgraded plants are functioning optimally and in line with the intended goals of improving efficiency, increasing energy output, and reducing environmental impacts. This requires the establishment of rigorous monitoring systems that continuously assess the performance of turbines, generators, and other mechanical components, as well as the overall output of the plants.

Real-time data collection and analysis will play a crucial role in the post-retrofit monitoring process. By leveraging advanced sensor technologies and data analytics platforms, plant operators can gain insights into the operational status of equipment, water flow management, and grid integration. This data can then be used to optimize the plants' performance over time, ensuring that any issues are identified and resolved quickly, thereby minimizing downtime and maximizing efficiency. The monitoring systems should also track environmental indicators, such as water quality, sediment levels, and biodiversity health, to ensure that the plants are not negatively impacting local ecosystems. This ongoing evaluation is essential for meeting both national environmental standards and European Union regulations, such as the Water Framework Directive, which requires member states to maintain good ecological status in their water bodies.

In addition to monitoring performance, follow-up efforts should focus on evaluating the financial and economic outcomes of the retrofitting projects. Retrofitting hydropower plants represents a significant capital investment, and it is crucial to assess whether the financial returns from increased efficiency and energy production meet expectations. Cost-benefit analyses, including lifecycle assessments, will provide insight into the economic viability of the retrofits and inform future investment decisions in Romania's renewable energy infrastructure. By quantifying the long-term savings from reduced operational and maintenance costs, as well as the potential revenue from increased electricity production, stakeholders can evaluate the overall success of the retrofitting projects. Furthermore, this economic evaluation should take into account any savings from avoided greenhouse gas emissions, as these reductions may translate into carbon credits or other financial incentives under European and global climate frameworks.

Looking beyond immediate follow-up, Romania must also chart a clear course for the future development of its hydropower sector. The retrofitting of existing plants is an important step, but it should be viewed as part of a broader energy transition strategy that aligns with the country's goals of decarbonizing its energy system and meeting its commitments under the European Green Deal. As Romania continues to integrate more renewable energy sources, such as wind and solar, into its energy mix, the role of hydropower will evolve. Hydropower plants will become increasingly valuable as a means of balancing intermittent renewable energy generation and ensuring grid stability.

Another promising area for future development is the integration of digital technologies into hydropower operations. As the energy sector becomes increasingly digitalized, there is significant potential for Romania's hydropower plants to benefit from advancements in artificial intelligence (AI), machine learning, and predictive analytics. These technologies can be used to optimize plant operations, improve water management strategies, and reduce the environmental impact of hydropower production. For example, AI algorithms can analyse vast amounts of data from sensors and control systems to predict equipment failures before they occur, enabling operators to perform preventative maintenance and avoid costly breakdowns. Machine learning models can also be used to optimize water flows and turbine operations in real time, ensuring that the plants are running as efficiently as possible under varying hydrological conditions.

Hydropower retrofitting must also be aligned with Romania's broader energy strategy and its commitments under the European Union's energy and climate policies. The European Green Deal, which aims to make the EU climate-neutral by 2050, places a strong emphasis on renewable energy, energy efficiency, and the reduction of carbon emissions. Romania's hydropower sector will play a crucial role in achieving these objectives, but it will need to be part of an integrated approach that includes investments in other renewable energy sources, especially wind and solar. The country must continue to explore synergies between hydropower and other renewables, particularly in terms of grid integration and energy storage, to create a more resilient and sustainable energy system.

In the context of climate change, Romania's hydropower future will also need to account for the potential impacts of changing weather patterns and water availability. As discussed in previous chapters, climate change is expected to lead to more variable precipitation patterns and increased instances of drought in some regions of Romania, which could affect the reliability of water flows for hydropower generation. Therefore, future hydropower developments must be designed with climate resilience in mind. This could involve the construction of more flexible and adaptable infrastructure, such as multi-purpose reservoirs that can be used for both energy generation and water supply, as well as the adoption of water-saving technologies that minimize the use of water for hydropower production.

International collaboration will be an important element of Romania's hydropower future. As a member of the European Union, Romania is part of a broader effort to create an integrated and resilient European energy market. Cross-border energy cooperation, particularly in the form of shared hydropower resources and grid interconnections, will be crucial for optimizing the use of renewable energy across the continent. Romania has the potential to play a significant role in this process.

Education and workforce development will also be important for ensuring the long-term success of Romania's hydropower sector. As the country transitions to a more modern and technologically advanced hydropower system, there will be a growing need for skilled workers who are trained in the latest engineering, environmental, and digital technologies. Romania's universities, technical institutes, and vocational training programs will need to adapt their curricula to meet the demands of the evolving water energy sector, providing the next generation of engineers, technicians, and energy managers with the skills and multi-sectoral knowledge necessary to lead the country's hydropower modernization efforts while taking care of biodiversity.

The follow-up to Romania's hydropower retrofitting projects must be seen as part of a larger, ongoing process of modernization, optimization, and adaptation. Continuous monitoring and evaluation of retrofitted plants will ensure that the immediate goals of improved efficiency, reliability, and environmental sustainability are met. However, Romania must also look to the future and consider how its hydropower sector can continue to evolve in response to changing energy demands, biodiversity and climate conditions, and technological advancements. By investing in energy storage, digital technologies, decentralized energy systems, and international cooperation, Romania can position its hydropower sector as a cornerstone of its renewable energy strategy and a key contributor to its long-term energy security and sustainability goals.

In analyzing the potential for energy gains through the modernization of Romania's hydropower plants, it becomes evident that a targeted approach is crucial. By focusing on plants with lower-than-median efficiency and prioritizing those with higher installed power, greater energy output, longer operating times, or less efficient installations, the hydroenergy sector can maximize the benefits of such investments. The estimated energy increase of over 500 GWh, reaching 1100 GWh in a best-case scenario, highlights the significant impact that modernization can have on hydroenergy.

Appendix A. Data HPP

Nr. Crt / No.	Bazin/Basin	Cursul de apa/ River	Denumirea barajului/ Dam	Orasul cel mai apropiat/ Nearest town	Judetul/ County	Tipul barajului/ Dam type	Cota coronament/ Level of crown	Inaltime height (m) Baraj/Dam	Inaltime height (m) Dig /Dike	Debit mediu/ Average flow (m^3/s)	Volum lac/ Storage volume ($10^3\ m^3$)	Scopul acumularii/ Purpose of storage	Anul PIF / Year of commisioning	Denumirea centralei/ HPP	Tipul centralei/ Type of HPP	Cota / Level Amonte/ Downstream	Cota / Level Aval/ Upstream	Cadere/ Water fall	Nr. si tip agregat/ No. and type of aggregate	Debit instalat/ Installed flow (m^3/s)	Putere instalata/ Installed power (MW)	Energie medie/ Average output (GWh/an)	Anul PIF / Year of commissioning
178	Bistrita	Bistrita	Pingarati	Piatra Neamt	NT	PG/TE	367.5	28	18	50.5	6	H	1964	Pingarati	CB	364.5	350.15	14.35	2K	180	23	57	1964
179		Bistrita	Vaduri	Piatra Neamt	NT	PG/TE	352.1	27	12.5	50.5	5.6	H	1965	Vaduri	CD	349.5	324.5	25	2K	200	44	90	1966
180		Bistrita	Piatra Neamt	Piatra Neamt	NT	PG/TE	326.8	27	14.5	45.5	10	H	1963	Piatra Neamt	CB	323.9	308.9	15	2K	84	11	52	1964
181		Bistrita	Reconstructia	Piatra Neamt	NT	PG/TE	314.65	8.15	6.7	45.5	0.25	H	1961	Vanatori	CD	307.8	287	20.8	4K	84	14	63	1963
182		Bistrita	-	Piatra Neamt	NT	TE	288.5	-	4.5	45.5	-	H	1964	Roznov	CD	287	266.2	20.8	2K	84	14	63	1963
183		Bistrita	-	Piatra Neamt	NT	TE	267.5	-	7	49.1	-	H	1964	Zanesti	CD	266.2	246	20.2	2K	84	14	63	1964
184		Bistrita	-	Buhusi	BC	TE	247.5	-	6.5	49.1	-	H	1964	Costisa	CD	246	225.8	20.2	2K	84	14	64	1964
185		Bistrita	-	Buhusi	BC	TE	227.5	-	5.5	53.4	-	H	1964	Buhusi	CD	225.8	210.8	15	2K	84	11	50	1964
186		Bistrita	Racova	Buhusi	BC	PG/TE	213.5	20	13	53.4	7.7	HI	1965	Racova	CD	210	194.5	15.5	2K	180	23	60	1965
187		Bistrita	Girleni	Buhusi	BC	PG/TE	197.5	19	8.5	53.9	5.1	H	1965	Girleni	CD	194	179	15	2K	180	23	61	1964
188		Bistrita	Lilieci	Bacau	BC	PG/TE	181.2	19	13	53.9	7.4	H	1966	Lilieci	CD	177.7	162.3	15.4	2K	180	23	56	1966
189		Bistrita	Bacau	Bacau	BC	PG/TE	165	18	13	53.9	4.6	H	1966	Bacau	CD	161.5	141.5	20	4K	180	30	74	1966
191	Siret	Siret	Galbeni	Bacau	BC	PG/TE	145	24	11.5	64.9	39.6	HS	1983	Galbeni	CD	141	129	12	2K	330	29.15	78.5	1983
192		Siret	Racaciuni	Bacau	BC	PG/TE	133	29	14	67.6	103.7	HS	1984	Racaciuni	CD	129	110.7	18.3	2K	330	45	112.3	1985
193		Siret	Beresti	Sascut	BC	PG/TE	112.7	29	13.5	69.2	120.4	HS	1985	Beresti	CB	110.7	92	18.7	2K	330	43.5	105	1986
194		Siret	Calimanesti	Marasesti	VN	PG/TE	79	21.5	13	72.6	44.3	HIS	1992	Calimanesti	CB	75.5	62.5	13	2K	380	40	79	1993
195		Siret	Cosmesti	Marasesti	VN	PG/TE	66.5	21.5	10	45.1	17	HI	exec.	Cosmesti	CB	62.5	50.5	12	2K	380	40	73	exec.
196		Siret	Movileni	Focsani	VN	PG/TE	54.5	21.5	13	45.2	63.6	HI	exec.	Movileni	CB	50.5	38.5	12	4K	380	36	67	exec.
197	Prut	Prut	Stinca Costesti	Botosani	BT	PG/TE	102.5	47	39	75.3	1400	HCSF	1978	Stinca Costesti	CB	90.8	62.5	28.3	1K	65	15	65	1978
198	Dunare	Dunare	Portile de Fier I(Ro)	Turnu Severin	MH	PG/TE	72.5	60	32	2770	1450	HNCF	1971	Portile de Fier I(Ro)	CB	69.5	42.5	27	6K	4350	1050	5384	1970
199		Dunare	Portile de Fier II(Sb)	Vinju Mare	MH	PG/TE	46	34	20	2774	400	HNIF	1984	Portile de Fier II(Sb)	CB	41	33.5	7.5	8B	3360	216	1236	1984
200		Dunare	-	Vinju Mare	MH	-	-	-	-	-	-	-	-	Portile de Fier II(Ro)	CB	41	33.5	7.5	8B	3360	216	1236	1984
201		Dunare	Gogosu(Ro)	Vinju Mare	MH	PG	47.5	34	21	2774	300	HNIF	1984	Gogosu(Ro)	CB	41	33.5	7.5	2B	840	54	308	1984
202		Dunare	-	Vinju Mare	MH	-	-	-	-	-	-	-	-	Centrala suplim.(Sb)	CB	41	33.5	7.5	2B	840	54	308	1998
203		Canal CNE	-	Cernavoda	CT	-	-	-	-	-	-	-	-	Cernavoda	CD	14.9	7.5	7.4	4K	184	12.6	78	1989

Table A1. Data from Hidroconstuctia S.A.

Appendix B. The United States' take on retrofitting and modernization

The United States is embarking on an unprecedented energy modernization initiative, spanning 33 states and backed by $430 million in funding. This effort, led by the Department of Energy () under the Biden-Harris administration, plans to revitalize 293 aging hydroelectric power facilities [6]. The upgrades aim to enhance not only the efficiency of these plants DOE but also address critical issues such as grid stability, dam safety, environmental concerns, and overall grid reliability, marking a significant milestone in modernizing the country's hydroelectric infrastructure.

The objective of this U.S. initiative is not to expand hydropower capacity but to optimize existing installations. The focus will be on improving dams, power infrastructure, and environmental safeguards. The upgrades, including advanced turbines, control systems, cables, and transformers, will make the hydroelectric plants more resilient to operational stress and external factors like storms and extreme temperatures. Of the $430 million investment, a portion will go towards reinforcing grid reliability and dam safety at hydroelectric stations nationwide. The DOE plans to replace key components, such as turbines and generators, ensuring enhanced power reliability. Overall, 149 projects will target dam safety, while 84 will focus on strengthening grid resilience.

This modernization plan also addresses the growing risks posed by climate change. Many dams are vulnerable to extreme weather conditions, and the initiative includes improvements to emergency spillways, gates, and water delivery systems to help them withstand heavy rainfall and prevent disasters. The program also entails concrete repairs and erosion control to fortify dam structures, ensuring the safety of critical energy assets. Additionally, these upgrades will extend the lifespan of hydroelectric plants, contributing to the stability of the energy grid. This is particularly important for states like California and New York, where hydropower plays a significant role and where climate-related risks, such as wildfires and storms, are on the rise. By maintaining these facilities, the U.S. can avoid blackouts and maintain a steady flow of renewable energy.

Beyond grid reliability, the U.S. modernization program is designed to minimize the environmental impacts of hydropower and improve recreational opportunities around dams. A total of 60 environmental projects will focus on protecting watercourses, improving aquatic habitats, and enhancing water quality. One key environmental effort involves installing fish passage systems, such as fish ladders, to help species navigate dams without being harmed, a critical measure for preserving biodiversity and supporting Indigenous communities. Advanced turbine designs will also reduce oxygen depletion in water and improve downstream water quality, benefiting aquatic ecosystems.

While federal funding is a key driver of this initiative, the DOE's $430 million is only part of a larger investment plan. The program will be supplemented by over $2.38 billion in private sector investment, demonstrating strong interest from private companies in maintaining and developing the nation's hydroelectric resources. Major energy companies like Southern Co., PG&E Corp., and PacifiCorp are among the recipients of these federal funds, reflecting the public-private partnerships that form the foundation of this modernization effort [6].

As the U.S. transitions to renewable energy, hydropower remains a crucial component. Hydroelectric power currently accounts for 93% of all utility-scale energy storage in the country and is poised to serve as a foundational technology that supports the expansion of newer renewable energy sources like wind and solar. These hydroelectric upgrades will contribute to energy storage capacity and power grid stability, increasing the flexibility and reliability of the nation's energy system [6].

An important component in such analyses is the classification of large hydropower plants. The U.S. Department of Energy (DOE) classifies large hydropower plants as establishments with a capacity of more than 30 megawatts (MW), while the EU classifies them as establishments with installed power ≥ 10 MW

Appendix C. Technical details

Key Concepts and Formulas:

- **Hydroelectric Energy:** This is the energy derived from the movement of water.

To produce electrical energy, it is necessary to transform the potential energy of water into mechanical energy, which is then converted into electrical energy.

If we consider a fluid, the equation can be written as:

The equation $E = \alpha v^2/2g + p/\gamma + z$ represents the specific energy of a fluid, where:

- E: Specific energy
- α: Correction factor for non-uniform velocity distribution
- v: Velocity of the fluid
- g: Acceleration due to gravity
- p: Pressure of the fluid
- γ: Specific weight of the fluid
- z: Elevation head

Considering two points, the energy that can be collected between these two points is:

- $\Delta E = E_1 - E_2 = \left(\frac{\alpha_1 v_1^2}{2g} + \frac{p_1}{\gamma} + z_1\right) - \left(\frac{\alpha_2 v_2^2}{2g} + \frac{p_2}{\gamma} + z_2\right)$

- **Head (H=** z_1- z_2**):** The difference in elevation between two points in a fluid flow. It represents the potential energy per unit weight of the fluid.

- **Mechanical Work (L):** The work done by a force over a distance. In the context of hydroelectricity, it's the work done by the force of gravity on a mass of water as it falls through a height.
  - $L = G \cdot H$
  - G: weight of the fluid

- **Power (P):** The rate at which work is done.
  - $P = dL/dt = \eta \cdot \gamma \cdot Q \cdot H$
  - *Q:* Flow rate
  - *H:* Head
  - η – the efficiency of hydropower plant

- **Energy (E):** The energy.

- $E = \int_0^{1yr} P(t)dt = \int_0^{1yr} \eta(Q(t), H(Q(t)))\cdot\gamma\cdot Q(t)\cdot H(Q(t))dt$

- $E \approx \eta_g \cdot\gamma\cdot Q_m \bullet H_m \bullet T_{fm}$, energy in average hydrological year

where, H_m represents the average head, T_{fm} is the operating time at the multiannual average flow and Q_m is the multiannual average flow.

- $E \approx \eta_g \bullet \gamma \bullet Q_i \bullet H_n \bullet T_{fi}$, energy at the installed flow rate

where, H_n represents the net head, T_{fi} is the operating time at the installed flow and Q_i is the installed flow.

The integral E represents the energy generation of a hydropower plant over a one-year period. Here's a breakdown of its components.

- E, represents the total energy generated over one year.

- η, is the efficiency of the hydropower plant.

- H(Q(t)), is the head (height difference between the level water of the water intake and the turbine) as a function of discharge (Q) at time t, considering hydraulic loss energy.

- Q(t), is the discharge (flow rate of water) at time t.

− γ, is the volumetric weight of water.

The integral essentially sums up the energy produced at each instant (dt) over the entire year. At each instant, the energy generated is proportional to the product of the head, discharge, and the efficiency of the plant. Integrating this over time gives the total energy produced.

Several strategies can be used to modernize hydropower plants and maximize power generation, and here are a few examples:

i. Upgrading Turbines by increasing efficiency improvements

ii. Optimizing operation, namely, real-time monitoring and control, predictive maintenance, and expanding storage capacity. Advanced control systems can monitor water levels, flow rates, and turbine performance in real-time. This enables optimal operation based on changing conditions, maximizing energy production. By analysing sensor data and historical performance, predictive maintenance can identify potential issues before they lead to downtime, ensuring continuous operation. Storing water in the reservoir and using it during peak demand can significantly increase the financial value of the energy.

Modernization should be done with a focus on minimizing environmental impact.

The hydropower plant's operation should be optimized to integrate seamlessly with the grid, considering factors like grid stability and demand fluctuations.

By implementing these strategies, hydropower plants can significantly increase their energy output, making them even more valuable contributors to a sustainable energy future.

Hydroelectric Power Plant
The specific devices and their configurations vary depending on the type of hydroelectric plant (storage, run-of-river, diversion) and the water head available.
Figure 1 shows a simplified representation of a hydroelectric plant, and actual plants may have additional or more complex components.
As seen in the image, the different machines and equipment present in hydroelectric facilities are listed below, along with their purposes:

I. Damming section:
Barrage, weir (for run-of-river plants) or combination of barrage and weir (for diversion plants). Run-of-river is a type of hydropower project in which limited storage capacity is available and water is released at roughly the same rate as the natural flow of the river.
II. Spillway for controlling the maximum permissible headwater level and discharges excess water during floods.
III. The upper basin (reservoir) because of the dam or the weir.
IV. Intake Structure directs water from the reservoir to the penstock.
V. Supply piping carries water from the intake structure to the turbines. These can be tunnels, penstocks, or open channels.
VI. A surge-relieving device that dampens pressure fluctuations in the penstock. These can be surge tanks (for high-head plants) or bypass outlets (for rapid shutdowns).
VII. A powerhouse houses the turbines and generators that convert water energy into electricity. These can be hall designs or chamber designs, where the location can be underground or outdoor, at the base or interior of a barrage, on a riverbank.
VIII. Tail water section:
For discharges water from the turbines back into the river. Design depends on powerhouse location, turbine type, topography, and degree of exploitation of the scheme. The specific devices and their configurations vary depending on the type of hydroelectric plant (storage, run-of-river, diversion) and the water head available.

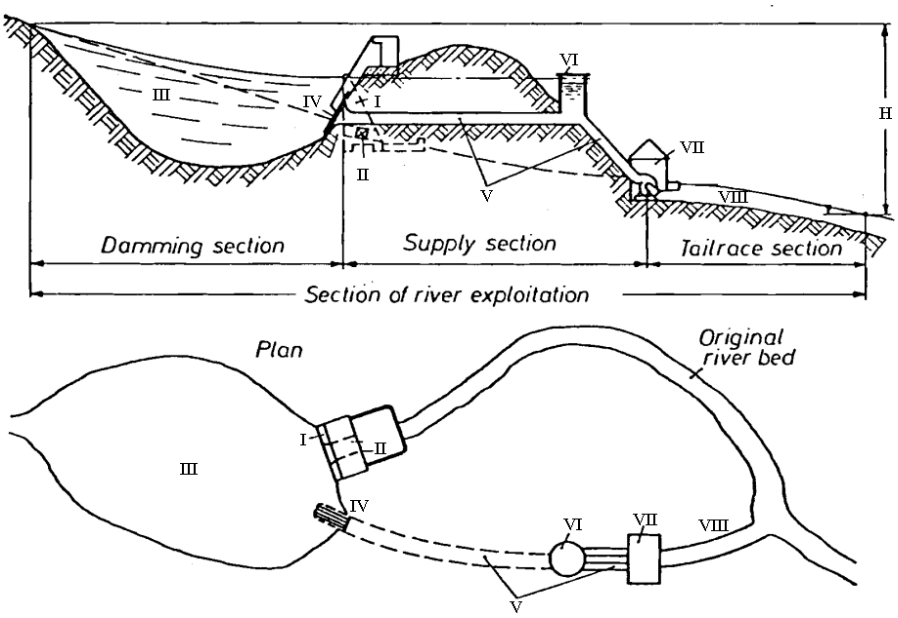

Figure 1. Elevation and plan of characteristic components of diversion river power plant along its section of exploitation [9].

This schematic illustrates the flow of water through a turbine-driven generator system, emphasizing control mechanisms for water flow (valves), power generation components (turbine and generator), and the routing of water from the source to the outflow. The elements represent essential parts of a hydropower system that work together to generate electricity by utilizing the mechanical energy of flowing water.

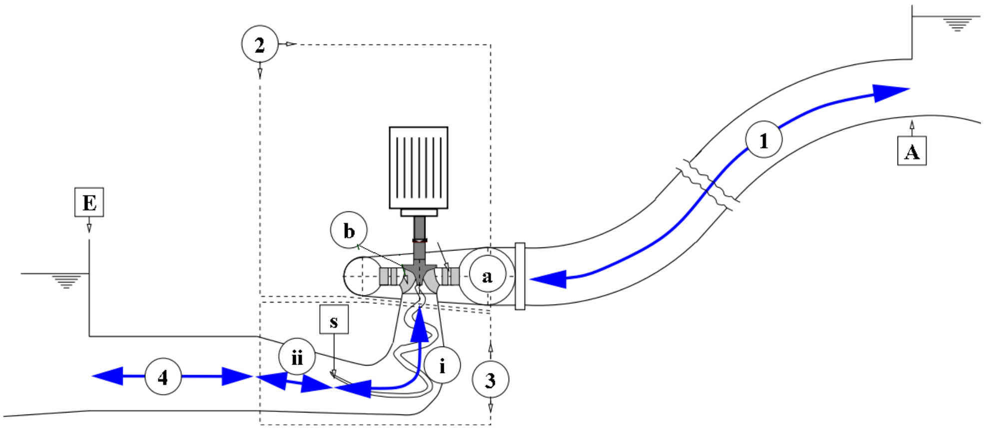

Figure 2. Detailed scheme of a hydroelectric system [10]

A hydroelectric power plant typically includes:

- (1) Penstock - this usually represents the main water flow path, which transports water from the reservoir (or source) down towards the turbine. The blue arrow indicates the direction of water flow;

- (2) Electrical Generator - this part is connected to the turbine and generates electricity when the turbine rotates due to the force of water passing through it;

- (3) Turbine - the turbine converts the kinetic energy of the water into mechanical energy, which then drives the connected generator. The water enters at point "a" and exits at "b" after rotating the turbine;

- (4) Tailrace or Outflow - this is the water's exit path, leading the water away from the turbine back into a river or downstream reservoir after it has passed through the turbine;

- (A) Water Source Level - this represents the height of the water source (e.g., a dam with reservoir or water intake). The height difference (head) is a critical factor for the amount of potential energy converted into mechanical energy;

- (E) Grounding or Electrical Reference - this symbol indicates an electrical grounding point, ensuring the system's electrical safety;

- (i) Valve or Gate Mechanism - this may represent a valve that regulates the flow of water to the turbine. Adjusting this valve controls how much water enters the turbine, affecting the power output;

- (ii) Control System for Valve - this could represent a secondary control mechanism for the valve, often related to hydraulic or mechanical systems that assist in the precise movement or regulation of the valve;

- (b) Turbine Exit or Draft Tube - this is where the water exits the turbine after generating power. It usually leads to the tailrace, where the water is safely redirected downstream;

- (a) Turbine Inlet - this is the point where water enters the turbine;

- (i) Cavitating vortex - area where cavitation phenomena can occur, influencing the efficiency of the turbine, in reaction turbines (Kaplan, Francis);

▪ (ii) Non-torque side - area with more stable flow [11].

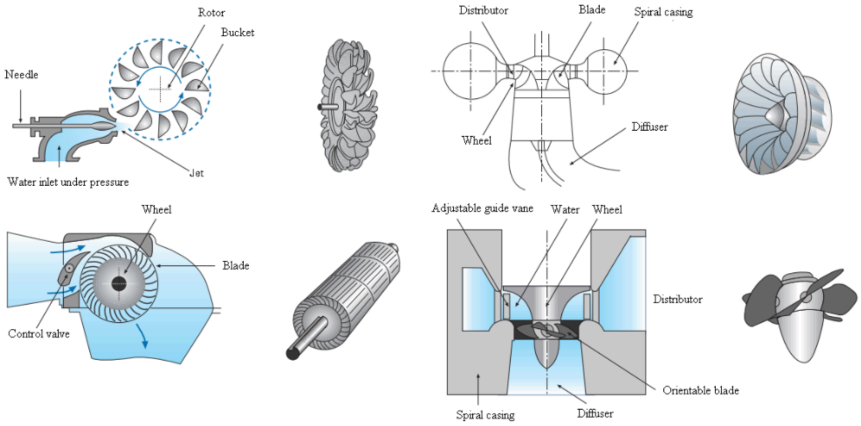

Figure 3. Components of turbines.

References

1. https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Europe/Romania_Europe_RE_SP.pdf.
2. Emanuele Quaranta, George Aggidis, Robert M. Boes, Claudio Comoglio, Carlo De Michele, Epari Ritesh Patro, Evgeniia Georgievskaia, Atle Harby, Ioannis Kougias, Sebastian Muntean, Juan Pérez-Díaz, Pedro Romero-Gomez, Marco Rosa-Clot, Anton J. Schleiss, Elena Vagnoni, Markus Wirth, Alberto Pistocchi, Assessing the energy potential of modernizing the European hydropower fleet, Energy Conversion and Management, Volume 246, 2021, 114655, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2021.114655.
3. Bortoni, E.; Souza, Z.d.; Viana, A.; Villa-Nova, H.; Rezek, Â.; Pinto, L.; Siniscalchi, R.; Bragança, R.; Bernardes, J., Jr. The Benefits of Variable Speed Operation in Hydropower Plants Driven by Francis Turbines. Energies 2019, 12, 3719. https://doi.org/10.3390/en12193719
4. Kumar, A., T. Schei, A. Ahenkorah, R. Caceres Rodriguez, J.-M. Devernay, M. Freitas, D. Hall, Å. Killingtveit, Z. Liu, 2011: Hydropower. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
5. Hydropower – Practice and Application, Edited by Hossein Samadi-Boroujeni, Croatia, 2012. ISBN 978-953-51-0164-2
6. https://www.ecoticias.com/en/energy-hydropower-doe-america/7435/
7. https://sdgs.un.org/basic-page/global-stakeholders-online-consultation-sdg-7-review-2023-hlpf-51226.
8. Udochukwu B. Akuru, Ifeanyichukwu E. Onukwube, Ogbonnaya I. Okoro, Emeka S. Obe, Towards 100% renewable energy in Nigeria, Renewable and Sustainable Energy Reviews, Volume 71, 2017, Pages 943-953, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2016.12.123.
9. Raabe, J. Hydro Power: The Design, Use, and Function of Hydromechanical, Hydraulic, and Electrical Equipment. Editor: International Publishers Service Incorporated, 1985. VDI-Verlag GmbH. ISBN 9783184006167
10. Blommaert, G. Étude du Comportement Dynamique Des Turbines Francis: Contrôle Actif de Leur Stabilité de Fonctionnement. Ph.D. Thesis, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, 2000.
11. Ioan Anton, "Turbine hidraulice", Editura Facla, Timişoara 1979
12. Hydropower – Practice and Application, Edited by Hossein Samadi-Boroujeni, Croatia, 2012. ISBN 978-953-51-0164-2
13. Hidroelectrica , #1Power Producer in Romania and One of the Largest European Hydro Companies, 9M, 2023, Key Financials Update, 15.11.2023, https://cdn.hidroelectrica.ro/cdn/ipo/prezentari/231115_h2o_en_q32023-financial-results-presentation.pdf.
14. Shukri Yah, A.,Md Nor, N.,Rohashikin, N.,Azam Ramli, N.,Ahmad, F. and Zia UlSau, A. (2012) Determination of the probability plotting position for type i extreme value distribution. Journal of Applied Sciences, 12, 1501–1506.

15. Gyanendra Tiwari, Jitendra Kumar, Vishnu Prasad, Vivek Kumar Patel, Utility of CFD in the design and performance analysis of hydraulic turbines — A review, Energy Reports, Volume 6, 2020, Pages 2410-2429, ISSN 2352-4847, https://doi.org/10.1016/j.egyr.2020.09.004.
16. Ioannis Kougias, George Aggidis, François Avellan, Sabri Deniz, Urban Lundin, Alberto Moro, Sebastian Muntean, Daniele Novara, Juan Ignacio Pérez-Díaz, Emanuele Quaranta, Philippe Schild, Nicolaos Theodossiou, Analysis of emerging technologies in the hydropower sector, Renewable and Sustainable Energy Reviews, Volume 113, 2019, 109257, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2019.109257.
17. Khalid A. Khan, Md Muzakkir Quamar, Faleh H. Al-Qahtani, Muhammad Asif, Mohammed Alqahtani, Muhammad Khalid, Smart grid infrastructure and renewable energy deployment: A conceptual review of Saudi Arabia, Energy Strategy Reviews, Volume 50, 2023, 101247, ISSN 2211-467X, https://doi.org/10.1016/j.esr.2023.101247.
18. Hossein Saber, Hesam Mazaheri, Hossein Ranjbar, Moein Moeini-Aghtaie, Matti Lehtonen, Utilization of in-pipe hydropower renewable energy technology and energy storage systems in mountainous distribution networks, Renewable Energy, Volume 172, 2021, Pages 789-801, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2021.03.072.
19. IRENA (2012), Renewable Energy Technologies: Cost Analysis Series, International Renewable Energy Agency, Volume 1: Power Sector, Issue 3/5, Hydropower
20. https://e360.yale.edu/features/can-retrofitting-dams-for-hydro-provide-a-green-energy-boost
21. Rehabilitation of hydropower, Water Papers, Joseph Goldberg, Oeyvind Espeseth Lier 2011, World Bank Document;https://documents1.worldbank.org/curated/en/518271468336607781/pdf/717280WP0Box370power0for0publishing.pdf
22. Yuguda, Taitiya & Li, Yi & Xiong, Wei & Zhang, Wenlong. (2020). Life cycle assessment of options for retrofitting an existing dam to generate hydro-electricity. The International Journal of Life Cycle Assessment. 25. 10.1007/s11367-019-01671-1.
23. Paolo Bragolusi, Chiara D'Alpaos, The valuation of buildings energy retrofitting: A multiple-criteria approach to reconcile cost-benefit trade-offs and energy savings, Applied Energy, Volume 310, 2022, 118431, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2021.118431.
24. https://www.profit.ro/povesti-cu-profit/energie/hidroelectrica-a-anulat-megalicitatia-de-100-milioane-euro-pentru-retehnologizarea-vidraru-la-care-se-inscrisese-si-cel-mai-bogat-om-din-rusia-16886350
25. https://www.profit.ro/povesti-cu-profit/energie/video-contractul-pentru-retehnologizarea-hidrocentralei-vidraru-investitie-de-peste-200-de-milioane-de-euro-semnat-unul-dintre-cele-mai-emblematice-obiective-hidroenergetice-din-romania-21661110
26. https://www.wall-street.ro/articol/Companii/99815/Cum-arata-hidrocentrala-de-la-Lotru-Ciunget-dupa-o-retehnologizare-de-88-mil-euro.html
27. https://www.enpg.ro/category/publications/energy-decarbonisation/
28. https://openrivers.eu/wp-content/uploads/2023/09/Gough-et-al-2018-Dam-Removal-Europe-report.pdf
29. William M. Twardek, Ian G. Cowx, Nicolas W.R. Lapointe, Craig Paukert, T. Douglas Beard, Elena M. Bennett, David Browne, Andrew K. Carlson, Keith D. Clarke, Zeb Hogan, Kai Lorenzen, Abigail J. Lynch, Peter B. McIntyre, Paulo Pompeu, Mark Rogers, Alexis Sakas, William W. Taylor, Taylor D. Ward, Zeenatul Basher, Steven J. Cooke, Bright spots for inland fish and fisheries to guide future hydropower development, Water Biology and Security, Volume 1, Issue 1, 2022, 100009, ISSN 2772-7351, https://doi.org/10.1016/j.watbs.2022.100009.
30. WCD, World Commision on Dams 2001
31. Moore, Deborah & Dore, John & Gyawali, Dipak. (2010). The World Commission on Dams + 10: Revisiting the Large Dam Controversy. Water Alternatives. 3.
32. Lizica Simona Paraschiv, Spiru Paraschiv, Contribution of renewable energy (hydro, wind, solar and biomass) to decarbonization and transformation of the electricity generation sector for sustainable development, Energy Reports, Volume 9, Supplement 9, 2023, Pages 535-544, ISSN 2352-4847, https://doi.org/10.1016/j.egyr.2023.07.024.
33. https://www.infoclima.ro/starea-climei-ro-2024.
34. Dejeu, Calin & Carpa, Rahela. (2020). Ecological Impact of Hydropower Building Yards in Romania.
35. Alban Kuriqi, António N. Pinheiro, Alvaro Sordo-Ward, María D. Bejarano, Luis Garrote, Ecological impacts of run-of-river hydropower plants—Current status and future prospects on the brink of energy transition, Renewable and Sustainable Energy Reviews, Volume 142, 2021, 110833, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2021.110833.
36. Nusrat Jahan Bipa, Giulia Stradiotti, Maurizio Righetti, Giuseppe Roberto Pisaturo, Impacts of hydropeaking: A systematic review, Science of The Total Environment, Volume 912, 2024, 169251, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2023.169251.
37. Kondolf, george 'mathias & Gao, Yongxuan & Annandale, George & Morris, Gregory & Jiang, Enhui & Zhang, Junhua & Cao, Yongtao & Carling, Paul & Fu, Kaidao & Guo, Qingchao & Hotchkiss, Rollin & Peteuil, Christophe & Sumi, Tetsuya & Wang, Hsiao-Wen & Wang, Zhongmei & Wei, Zhilin & Wu, Baosheng & Wu, Caiping & Yang, Chih. (2014). Sustainable Sediment Management in Reservoirs and Regulated Rivers: Experiences from Five Continents. Earth's Future. 10.1002/2013EF000184.

38. UNESCO World Heritage Convention, https://whc.unesco.org/en/list/588/
39. Tomczyk, Paweł & Wiatkowski, Mirosław. (2021). Impact of a small hydropower plant on water quality dynamics in a diversion and natural river channel. Journal of Environmental Quality. 50. 1156-1170. 10.1002/jeq2.20274.
40. Kim, J.; Kwak, J.; Ahn, J.M.; Kim, H.; Jeon, J.; Kim, K. Oscillation Flow Dam Operation Method for Algal Bloom Mitigation. *Water* **2022**, *14*, 1315. https://doi.org/10.3390/w14081315
41. Killingtveit, Ånund & Adera, Abebe. (2017). Climate Change and impact on Water Resources and Hydropower The case of Vanatori Neamt in the Carpathian region of Romania. 10.13140/RG.2.2.33697.61281.
42. Jánosi, I.M.; Bíró, T.; Lakatos, B.O.; Gallas, J.A.C.; Szöllosi-Nagy, A. Changing Water Cycle under a Warming Climate: Tendencies in the Carpathian Basin. *Climate* **2023**, *11*, 118. https://doi.org/10.3390/cli11060118
43. https://www.infoclima.ro/starea-climei-ro-2024
44. Turner, Sean & Ng, Jia & Galelli, Stefano. (2017). Examining global electricity supply vulnerability to climate change using a high-fidelity hydropower dam model. Science of The Total Environment. 590. 10.1016/j.scitotenv.2017.03.022.
45. Igor Iliev, Chirag Trivedi, Ole Gunnar Dahlhaug, Variable-speed operation of Francis turbines: A review of the perspectives and challenges, Renewable and Sustainable Energy Reviews, Volume 103, 2019, Pages 109-121, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2018.12.033.
46. J.P. Dedieu, A. Lessard-Fontaine, G. Ravazzani, E. Cremonese, G. Shalpykova, M. Beniston, Shifting mountain snow patterns in a changing climate from remote sensing retrieval, Science of The Total Environment, Volume 493, 2014, Pages 1267-1279, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2014.04.078.
47. Șmuleac, L.; Rujescu, C.; Șmuleac, A.; Imbrea, F.; Radulov, I.; Manea, D.; Ienciu, A.; Adamov, T.; Pașcalău, R. Impact of Climate Change in the Banat Plain, Western Romania, on the Accessibility of Water for Crop Production in Agriculture. *Agriculture* **2020**, *10*, 437. https://doi.org/10.3390/agriculture10100437.
48. IHA, International Hydropower Association. 2015 Hydropower status report. IHA, 2015.
49. Hamududu, B. , Killingtvelt, A. Assessing climate change impacts on global Hydropower. Energies 2012; 5: 305-322.
50. IEA, International Energy Agency. Technology roadmap: hydropower. IEA, 2012.
51. WEC, World Energy Council. World energy resources: charting the upsurge in hydropower development 2015. WEC, London, UK, 2015.
52. Kaygusuz, K. 2016. Hydropower as clean and renewable energy source for electricity generation. Journal of Engineering Research and Applied Science. 5, 1 (Jun. 2016), 359-369.
53. IEA, International Energy Agency. World energy outlook 2014. IEA, Paris, 2014.
54. Zujian Huang, Hao Zhou, Zhijian Miao, Hao Tang, Borong Lin, Weimin Zhuang, Life-Cycle Carbon Emissions (LCCE) of Buildings: Implications, Calculations, and Reductions, Engineering, Volume 35, 2024, Pages 115-139, ISSN 2095-8099, https://doi.org/10.1016/j.eng.2023.08.019.
55. Bridget R. Deemer, John A. Harrison, Siyue Li, Jake J. Beaulieu, Tonya DelSontro, Nathan Barros, José F. Bezerra-Neto, Stephen M. Powers, Marco A. dos Santos, J. Arie Vonk, Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis, *BioScience*, Volume 66, Issue 11, 1 November 2016, Pages 949–964, https://doi.org/10.1093/biosci/biw117
56. Zilin, Wang & Chan, Faith & Feng, Meili & Johnson, Matthew. (2024). Greenhouse gas emissions from hydropower reservoirs: emission processes and management approaches. Environmental Research Letters. 19. 10.1088/1748-9326/ad560c.
57. Ministy of Energy, National Hydrogen Strategy and Action Plan 2023-2030, https://energie.gov.ro/wp-content/uploads/2023/05/EN-Proiect-National-Hydrogen-Strategy.pdf
58. European Comission, The 2021-2030 Integrated National Energy and Climate Plan April 2020, https://energy.ec.europa.eu/system/files/2020-06/ro_final_necp_main_en_0.pdf
59. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora, https://eur-lex.europa.eu/eli/dir/1992/43/oj
60. Ezeh, Michael & Ogbu, Adindu & Ikevuje, Augusta Heavens & George, Emmanuel. (2024). Stakeholder engagement and influence: Strategies for successful energy projects. International Journal of Management & Entrepreneurship Research. 6. 2375-2395. 10.51594/ijmer.v6i7.1330.
61. Cvijović, Jelena & Obradović, Vladimir & Todorovic, Marija. (2021). Stakeholder Management and Project Sustainability—A Throw of the Dice. Sustainability. 13. 9513. 10.3390/su13179513.
62. Faria, Felipe & Davis, Alex & Severnini, Edson & Jaramillo, Paulina. (2017). The local socio-economic impacts of large hydropower plant development in a developing country. Energy Economics. 67. 10.1016/j.eneco.2017.08.025.
63. Hydroelectric Power A Guide for Developers and Investors, International Finance Corporation, World Bank Group
64. Bal, Menoka & Bryde, David & Fearon, Damian & Ochieng, Edward. (2013). Stakeholder Engagement: Achieving Sustainability in the Construction Sector. Sustainability. 6. 695-710. 10.3390/su5020695.
65. Reynolds, Samantha. (2024). Stakeholder Engagement and its Impact on Supply Chain Sustainability in the Context of Renewable Energy. 10.20944/preprints202406.0080.v1.

66. Lučin, I.; Sikirica, A.; Šiško Kuliš, M.; Čarija, Z. Investigation of Efficient Optimization Approach to the Modernization of Francis Turbine Draft Tube Geometry. Mathematics 2022, 10, 4050. https://doi.org/10.3390/math10214050
67. Lazarevikj, Marija & Stojkovski, Filip & Stojkovski, Valentino & Markov, Zoran. (2020). Small scale variable speed Francis turbines: possibilities and challenges.
68. Liu, Zhengxuan & Sun, Ying & Xing, Chaojie & Jia, Liu & He, Yingdong & Zhou, Yuekuan & Zhang, Guoqiang. (2022). Artificial intelligence powered large-scale renewable integrations in multi-energy systems for carbon neutrality transition: Challenges and future perspectives. Energy and AI. 10. 100195. 10.1016/j.egyai.2022.100195.
69. Raza, Falsk. (2023). AI for Predictive Maintenance in Industrial Systems. 10.13140/RG.2.2.27313.35688.
70. Kougias I. 2019. Hydropower technology development report 2018. EUR 29912 EN.
71. Gabriel Năstase, Alexandru Şerban, Alina Florentina Năstase, George Dragomir, Alin Ionuţ Brezeanu, Nicolae Fani Iordan, Hydropower development in Romania. A review from its beginnings to the present, Renewable and Sustainable Energy Reviews, Volume 80, 2017, Pages 297-312, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2017.05.209.
72. Lia L, Aas MN, Killingtveit Å. Increased generation from upgrading and extension projects. Int J Hydropower Dams 2017;24(4):75–8.
73. Terrier S, Jordan F, Schleiss AJ, Haeberli W, Huggel C, Künzler M. Optimized and adapted hydropower management considering glacier shrinkage scenarios in the Swiss Alps. In: Schleiss Boes, editor. Proc. of international symposium on dams and reservoirs under changing challenges – 79th annual meeting of ICOLD – Swiss Committee on Dams; 2011.
74. Haeberli W, Buetler M, Huggel Ch, Lehmann Friedli T, Schaub Y, Schleiss AJ. New lakes in deglaciating high-mountain regions – opportunities and risks. Clim Change 2016;139:201–14. https://doi.org/10.1007/s10584-016-1771-5
75. Schaefli B, Manso P, Fischer M, Huss M, Farinotti D. The role of glacier retreat for Swiss hydropower production. Renewable Energy 2019;132:616–27.
76. Nogueira HI, Pfister M, Schleiss AJ. Approaches to reduce friction losses in headrace waterways of hydropower plants. J Hydraul Eng 2016;142(5): 02516001. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001123.
77. Vereide K, Svingen B, Guddal R, Engineer SH. Case study: Damaging effects of increasing the installed capacity in an existing hydropower plant. Proc. 12th international conference on pressure surges, fluid transients and water hammer, Dublin, Ireland. 2015.
78. Muntean S, Susan-Resiga R, Goede E, Baya A, Terzi R, Tîrs ̦i C. Scenarios for refurbishment of a hydropower plant equipped with Francis turbines. Renewable Energy Environ Sustain 2016;1(30):1–6. https://doi.org/10.1051/rees/2016030
79. Zuzanna Zajac, Beatriz Revilla-Romero, Peter Salamon, Peter Burek, Feyera A. Hirpa, Hylke Beck, The impact of lake and reservoir parameterization on global streamflow simulation, Journal of Hydrology, Volume 548, 2017, Pages 552-568, ISSN 0022-1694, https://doi.org/10.1016/j.jhydrol.2017.03.022.
80. Pasbani Khiavi, Majid, Sari, Ali, Evaluation of Hydrodynamic Pressure Distribution in Reservoir of Concrete Gravity Dam under Vertical Vibration Using an Analytical Solution, Mathematical Problems in Engineering, 2021, 6669366, 9 pages, 2021. https://doi.org/10.1155/2021/6669366.
81. Betti A, Crisostomi E, Paolinelli G, Piazzi A, Ruffini F, Tucci M. (2019). Condition monitoring and early diagnostics methodologies for hydropower plants. arXiv preprint arXiv:1911.06242.
82. YanmazAM,AriO.A study on dam instrumentation upgrading.KSCE J Civil Eng 2011; 15(2):317–25. https://doi.org/10.47260/jesge/1115.
83. Silva D, Carazas F, Souza G. Method to select instrumentation for hydraulic turbines in upgrading process. In: In 2009 international conference on computers & industrial engineering (IEEE); 2009. p. 1192–7.
84. Georgievskaia E. Limitations of modern diagnostic and prognostic systems for a hydraulic unit's health. Eng 2021;2(1):27–42. https://doi.org/10.3390/ eng2010003.
85. Kontoleontos E, Weissenberger S. Annual energy production maximization for tidal power plants with evolutionary algorithms. Int J Fluid Mach Systems 2017;10(3): 264–73. https://doi.org/10.5293/IJFMS.2017.10.3.264.
86. Zhang J, Chen D, Zhang H, Xu B, Li H, Aggidis GA, et al. Fast–slow dynamic behaviors of a hydraulic generating system with multi-timescales. J Vib Control 2019;25(23–24):2863–74. https://doi.org/10.1177/1077546319860306.
87. Paravan D, Stokelj T, Golob R. (2004). Improvements to the water management of a run-of-river HPP reservoir: methodology and case study. Control Eng Practice, 12(4), 377-385. 0.1016/S0967-0661(03)00106-0.
88. Cros K, Schleiss AJ, Artique G, Jordan F. Hydrological forecasting on glacier systems: temperature forecasting corrections. Proc. HYDRO 2016 Conference, Achievements, Opportunities and Challenges, 10-12 October 2016, Montreux, Switzerland. 2016.
89. Rosa-Clot M, Tina G. Floating PV plants. 1st Edition. Academic Press; 2020.
90. Silverio NM, Barros RM, Tiago Filho GL, Redon-Santafe M, dos Santos IFS, de Mello Valerio VE. Use of floating PV plants for coordinated operation with hydropower plants: Case study of the hydroelectric plants of the Sao Francisco River basin. Energy Convers Manage 2018;171:339–49. https://doi.org/10.1016/ j.enconman.2018.05.095.
91. International Renewable Energy Agency (IRENA), (2020). Innovation landscape brief: Innovative operation of pumped hydropower storage, Abu Dhabi.

92. Valavi M, Nysveen A. Variable-speed operation of hydropower plants: Past, present, and future. In: In 2016 XXII International Conference on Electrical Machines (ICEM); 2016. p. 640–6.
93. Iliev I, Tengs EO, Trivedi C, Dahlhaug OG. Optimization of Francis turbines for variable speed operation using surrogate modeling approach. J Fluids Eng 2020; 142(10):101214. https://doi.org/10.1115/1.4047675. 13 pages.
94. Huang X, Chamberland-Lauzon J, Oram C, Klopfer A, Ruchonnet N. Fatigue analyses of the prototype Francis runners based on site measurements and simulations. IOP Conf Series: Earth Environ Sci 2014;22(1):012014. https://doi.org/10.1088/1755-1315/22/1/012014.
95. Trivedi C, Gandhi B, Michel CJ. Effect of transients on Francis turbine runner life: a review. J Hydraul Res 2013;51(2):121–32. https://doi.org/10.1080/ 00221686.2012.732971.
96. Goyal R, Gandhi BK. Review of hydrodynamics instabilities in Francis turbine during off-design and transient operations. Renewable Energy 2018;116(Part A): 697–709. https://doi.org/10.1016/j.renene.2017.10.012.
97. Goldberg J,Espeseth Lier O. (2011). Rehabilitation of hydropower: an introduction to economic and technical issues. Water papers; World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/17251.
98. Brunes BT. Increasing power output from Francis turbines, Master Thesis. Trondheim, Norway: Norwegian University of Science and Technology; 2009.
99. Deschenes C, Fraser R, Fau JP. New trends in turbine modelling and new ways of partnership. In: Proc. 4th international conference on hydraulic efficiency measurement — IGHEM, Toronto, Ontario, Canada; 2002. p. 1–12.
100. Fust A, Ruoss R, Vogtli H, Vontobel J. Ausbau und Erneuerung des Rheinkraftwerkes Laufenburg. Wasser Energie Luft 1991;83(1/2):1–14.
101. Haury G, Kesselring P, Schrenk K, Reumschüssel Th, Biegen W, Bro ̈gelmann E. Rhneinkraftwerk Wyhlen-Ausbau und Erneuerung. Wasser Energie Luft 1993;85 (11/12):337–58.
102. Bieri S, Strauss P, Krebs P, Ender P, Peter M, Gisiger J-P, et al. Ausbau und Erneuerung des Kraftwerk Augst. Wasser Energie Luft 1994;86(3/4):59–102.
103. Reif H, Fust A. Neubau des Wehres und Kraftwerk Rheinfelden (New construction of the Rheinfelden weir and hydropwer plant). Wasserwirtschaft 2008;98(12): 12–7.
104. Anghel, C.G.; Ilinca, C. Hydrological Drought Frequency Analysis in Water Management Using Univariate Distributions. Appl. Sci. 2023, 13, 3055. https://doi.org/10.3390/app13053055.