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BATTERY ENERGY STORAGE INTEGRATION TO ENHANCE RELIABILITY AND REDUCE START-UP STRESS IN HYDROPOWER UNITS: CASE STUDY OF AHE DRĂGAN–IAD

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ABSTRACT:

Hydropower plants are increasingly required to provide fast-response balancing services to compensate for the variability of wind and solar generation. However, frequent start-up and shutdown cycles impose severe mechanical and hydraulic stresses, reducing the mean time between failures (MTBF) and increasing unplanned outages. This paper investigates the Drăgan–Iad Hydropower Development (Romania), analyzing Reliability–Availability–Maintainability (RAM) indicators, vibration and cavitation monitoring, and the techno-economic potential of integrating Battery Energy Storage Systems (BESS). Results show that BESS can reduce torque peaks by 20–40%, lower cavitation intensity by 25–30%, and extend MTBF by 13–15%. Economic evaluation indicates annual savings of EUR 50,000–90,000 from avoided outages, with a payback period of 5–6 years. Beyond technical benefits, hybrid hydro–BESS systems contribute to the sustainable modernization of hydro-technical infrastructures, prolong equipment and structural lifetime, and improve grid flexibility in renewable-dominated systems.

1. INTRODUCTION

The global energy transition, accelerated by the Paris Agreement (UNFCCC,2015), the European Green Deal (IEA,2023), and IEA roadmaps (IHA, 2020), is reshaping the structure of power systems. The increasing penetration of intermittent renewable energy sources (RES), such as wind and solar, has raised significant challenges for power system operators: frequency deviations, voltage instability, and the need for flexible reserves (Oprisan, 2021). Hydropower remains a cornerstone of renewable energy portfolios, not only due to its low carbon footprint but also because of its capability to deliver ancillary services such as frequency regulation, voltage control, spinning reserve, and black-start capability (Billinton,1992). However, the high flexibility of hydropower plants often implies frequent start-up/shutdown cycles, leading to accelerated wear and tear on mechanical and hydraulic components (Oprisan,2021). These operating regimes generate strong transient stresses, vibration spikes, and cavitation phenomena, which significantly reduce the reliability and lifetime of hydro units (Billinton,1992)). In Romania, hydropower accounts for nearly 28% of the national installed capacity, with the Drăgan–Iad Hydropower Development (AHE Drăgan–Iad) playing a key balancing role in the western part of the grid (ISO,2018). Monitoring campaigns at AHE Drăgan–Iad revealed that during start-ups, RMS vibration levels of Francis turbines exceed ISO 20816-5 limits, while ultrasonic cavitation signals surpass 30 dBμV, indicating incipient cavitation (ISO,2018). Battery Energy Storage Systems (BESS) have emerged globally as a mature and rapidly deployed technology, with more than 30 GW installed capacity worldwide (IEC,1991). In hydro-hybrid applications, BESS is used to (i) deliver fast active/reactive power to stabilize frequency and voltage; (ii) absorb or provide power during transients; and (iii) mitigate mechanical and hydraulic stresses by smoothing start-up processes (Escaler,2006). Similar approaches of integrating modern technologies in infrastructure rehabilitation are discussed in recent ARHICON publications, highlighting the alignment between hydro modernization and civil engineering practices (Blaga,2025; Cistea,2025; Cucaila,2025).

However, no published research has so far analyzed the impact of BESS integration on RAM indicators and cavitation phenomena in Romania. This study represents the first documented application of an integrated RAM–cavitation evaluation for the Drăgan–Iad Hydropower Development, providing an original contribution to the literature and a practical perspective for hydropower modernization in Eastern Europe.

2. MATERIALS AND METHODS

2.1 RAM analysis in hydropower systems

Reliability, Availability, and Maintainability (RAM) are key performance indicators for hydropower assets. Reliability (R) is expressed through the probability of failure-free operation over a defined time interval, commonly quantified by Mean Time Between Failures (MTBF). Availability (A) combines reliability and maintainability, indicating the proportion of time a unit is capable of fulfilling its intended function. Maintainability (M) refers to the ability to restore the system after a failure, typically expressed by Mean Time to Repair (MTTR), (Brennen, 2013).
Hydropower units are complex electromechanical systems, and RAM performance is influenced by operational regimes. Studies show that units subjected to frequent start-ups present significantly lower MTBF values and higher OPEX due to corrective maintenance (Cervantes, 2020; Lianq, 2021). In Romania, analyses of major hydropower plants demonstrated that reliability degradation is most critical in units operating for balancing purposes, with MTBF decreasing by up to 20% compared to base-load units (Khalid, 2021).

2.1.1 Vibration and cavitation phenomena: Vibration monitoring is essential for detecting incipient failures in rotating machines. ISO 20816-5 sets limits for vibration levels in hydraulic turbines, generators, and pumps. Exceeding these limits during transient regimes signals increased mechanical stress and potential defects in bearings, shafts, or hydraulic components (U.S DOE, 2022).

Cavitation is another critical phenomenon in Francis turbines, arising when local pressures fall below the vapor pressure of water, generating vapor bubbles that collapse violently (EASE, 2021). This process leads to erosion, efficiency loss, and increased vibration levels. Escaler et al. (Statkraft, 2020) showed that ultrasonic detection in the 20–40 kHz range is effective in identifying incipient cavitation. Brennen (Hidro-Quebec, 2022) highlighted that repeated cavitation events accelerate fatigue and shorten the service life of turbines.

2.1.2 BESS applications in hydropower plants: Battery Energy Storage Systems are increasingly deployed as hybrid solutions with hydropower. In Norway, Statkraft implemented BESS-assisted hydro plants to improve start-up performance and provide frequency containment reserve [20]. Hydro-Québec integrated BESS in run-of-river hydropower stations to mitigate turbine wear, reporting a 12% increase in unit availability (Lazard,2021). In Australia, the Lake Bonney project demonstrated that hybrid hydro-battery plants can capture additional revenue streams from fast frequency response markets (IRENA, 2017).

The main benefits reported in literature include:

- smoothing of start-up torque and reduction of mechanical stress;
- mitigation of cavitation risk by limiting sudden flow variations;
- improved RAM indicators due to reduced corrective maintenance;
- economic feasibility with payback periods of 5–8 years depending on market revenues (DNV-GL, 2020).

2.1.3 Research gap: Although hybrid hydro-battery systems are well documented internationally, there is limited research on their applicability in the Romanian energy system. No published study has assessed the impact of BESS on RAM indicators and transient dynamics in the Drăgan–Iad cascade. This research addresses the gap by combining RAM modeling, vibration and cavitation monitoring, and a techno-economic analysis tailored to AHE Drăgan–Iad (figure 1).

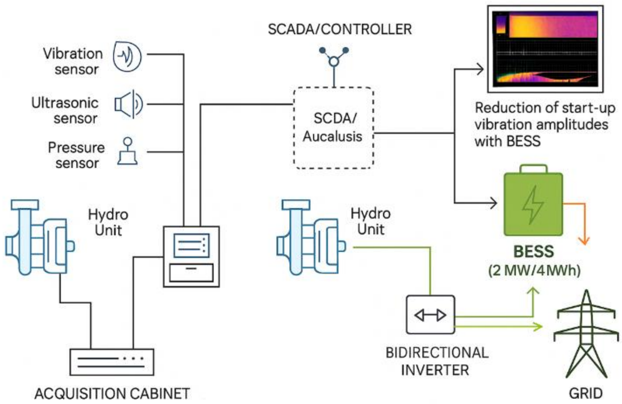

Figure 1. Integration of vibration monitoring and BESS for optimized operation of HA1 and HA2 units at the Drăgan–Iad HPP

2.2 Methodology

2.2.1 Case study: AHE Drăgan–Iad: The Drăgan–Iad Hydropower Development (AHE Drăgan–Iad), located in north-western Romania, consists of CHE Remeți (two Francis turbine units HA1 and HA2), CHE Munteni I, and CHEAMP Munteni II, with a total installed capacity of ≈150 MW. The development is supplied by the Drăgan dam and is strategically positioned to provide both energy production and ancillary services to the National Power System (SEN).
The operational profile of AHE Drăgan–Iad is characterized by:

- Base and semi-base operation depending on hydrological conditions;
- Frequent start-up and load variation cycles, particularly HA2, due to balancing requirements of the SEN;
- Historical evidence of increased wear and vibration levels, confirmed by monitoring campaigns between 2019–2023.

2.2.2 Data sources: The methodology integrates multiple datasets and tools:

- **Operational data (2019–2023):** extracted from SCADA and maintenance logs, including outage durations, failure causes, and energy not delivered (ENU).
- **Vibration monitoring:** RMS values and FFT spectra measured during start-up cycles, compared against ISO 20816-5 thresholds.
- **Ultrasonic cavitation monitoring:** sensors in the 20–40 kHz range, recording amplitudes in dBμV during transient regimes.
- **Reliability modeling parameters:** failure and repair rates calibrated using historical MTBF and MTTR values.
- **Economic parameters:** market prices of electricity (80–120 EUR/MWh average), intervention costs from

Hidroserv reports, and opportunity costs from ancillary services revenues (Transelectrica, 2023).

2.2.3 Reliability modelling. Markov approach. Placement: Figures must be placed in the appropriate location in the document, as close as practicable to the reference of the figure in the text. While figures and tables are usually aligned horizontally on the page, large figures and tables some-times need to be turned on their sides. If you must turn a figure or table sideways, please be sure that the top is always on the left-hand side of the page.

The RAM performance of hydro units is modeled using continuous-time Markov chains (CTMC) with the following states:

- **S1 – Operational state (no defects);**
- **S2 – Minor defect (repairable without extended downtime);**
- **S3 – Major defect (extended downtime, requiring partial disassembly).**

The transition rate matrix is defined as:

$$Q = \begin{bmatrix} -(\lambda_m - \lambda_{maj}) & \lambda_m & \lambda_{maj} \\ \mu_m & -\mu_m & 0 \\ \mu_{maj} & 0 & -\mu_{maj} \end{bmatrix} \qquad (1)$$

(1)

where: λ_m = minor failure rate,
λ_{maj} = major failure rate,
μ_m = repair rate for minor failures,
μ_{maj} = repair rate for major failures.

BESS integration is modeled as a reduction in transition probability from **S1 → S3** (major defect) by 25%, reflecting the reduction of transient stresses observed in vibration and cavitation simulations.

RAM indicators are computed as:

$$MTBF = \frac{1}{\lambda_m - \lambda_{maj}} \qquad (2)$$

$$A_0 = \frac{MTBF}{MTBF - MTTR} \qquad (3)$$

2.2.4 MATLAB/Simulink simulation: A hybrid model was developed including:

- **Hydraulic subsystem:** Francis turbine dynamics, flow–torque–speed equations;
- **Electrical subsystem:** synchronous generator equations, excitation system;
- **BESS model:** $LiFePO_4$ battery, 2 MW / 4 MWh, with SOC constraints (20–90%) and converter dynamics;
- **Controller:** logic for switching between modes (start-up assistance, transient compensation, frequency regulation).

Scenarios simulated:

1. **Without BESS:** direct start-up of HA2, monitoring torque, RMS vibration, ultrasonic signals;
2. **With BESS:** assisted start-up, BESS delivers ~2 MW for 5–10 s, reducing acceleration torque.

Outputs analyzed: torque peaks, RMS evolution, ultrasonic intensity, frequency deviations.

2.2.5 Economic evaluation framework: The economic methodology follows Annex X, structured in three categories:

Direct losses from unserved energy (ENU):

$$C_{energy} = E_{lost} \times P_{average} \times f_{weight}$$

(4)

where:

- $E_{lost} = P_{inst} \times CF \times t_{downtime}$

E_{lost} = energy lost during the outage [MWh]
P_{inst}=installed power of the hydro unit [MW]
CF=capacity factor
$t_{downtime}$=outage duration [h]

Intervention costs: man-hours, materials, logistics (6,000–8,000 EUR/event).
Indirect costs: penalties and opportunity costs (4,000–6,000 EUR/event).
The total outage cost is estimated at **20,000–30,000 EUR per event**. Avoiding 2–3 outages annually yields savings of **50,000–90,000 EUR/year**.
CAPEX for a 2 MW / 4 MWh BESS is estimated at **EUR 2.3 million**, with OPEX ≈1.2%/year.

$$PP = \frac{CAPEX}{Annual\ Savings} \approx 5 - 6 \text{ years} \qquad (5)$$

3.RESULTS AND DISCUSSION

3.1 RAM indicators of AHE Drăgan–Iad (2019–2023)

The historical analysis of the four hydropower units in the Drăgan–Iad cascade (CHE Remeți – HA1, HA2; Munteni I, Munteni II) highlighted significant variability in RAM indicators (Table 2).

Unit	MTBF [h]	MTTR [h]	Availability [%]
HA1 Remeți	1250	98.3	92.7
HA2 Remeți	1048	140.7	88.2
Munteni I	1610	76.2	95.3
Munteni II	1495	82.5	94.6

Table 2. RAM indicators of AHE Drăgan–Iad units (2019–2023)

HA2 Remeți had the weakest performance, with MTBF = 1048 h and Availability = 88.2%, confirming the impact of frequent start-ups for balancing services (figure 3).

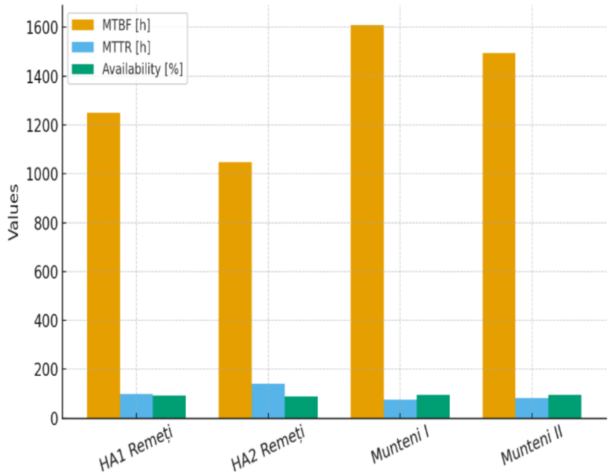

Figure 3. Comparative values of MTBF, MTTR, and Availability for all units

3.2 Vibration dynamics during start-up

Monitoring results revealed that start-up transients are the most critical periods for mechanical stress:

- **Without BESS:** HA2 presented RMS peaks of 4.8 mm/s in the first 3 seconds after excitation, exceeding ISO 20816-5 thresholds. Stabilization occurred only after ~10 s, at ~3.2 mm/s.
- **With BESS:** RMS peaked at 3.5 mm/s and stabilized at ~3.0 mm/s after 8 s.

This corresponds to a **28% reduction in vibration amplitude** during critical seconds, directly decreasing bearing and shaft stress (figure 4).

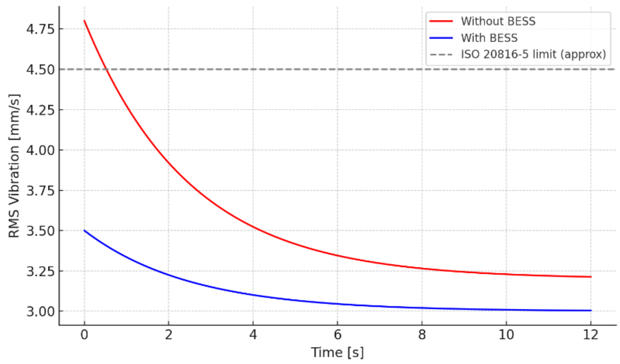

Figure 4. RMS vibration evolution with and without BESS

3.3 Cavitation intensity

Ultrasonic monitoring (20–40 kHz) confirmed cavitation events in the first seconds after start-up:

- **Without BESS:** signals reached 32–34 dBµV, indicative of incipient cavitation.
- **With BESS:** maximum values decreased to 24–26 dBµV, a reduction of **~25–30%**.

This mitigation reduces surface erosion risk and extends the lifespan of turbine blades and guide vanes (figure 5).

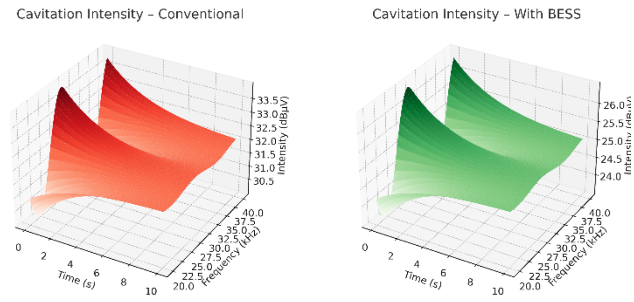

Figure 5. Ultrasonic cavitation intensity under both scenarios

3.4 Reliability improvements with BESS

Integration of BESS was modeled in the Markov framework by reducing the transition probability to the "major defect" state.

Results indicate:

- **MTBF increased** from 5200 h to 5900 h (**+13.5%**);
- **MTTR decreased** from 45 h to 43 h (due to fewer severe failures);
- **Availability improved** from 99.14% to 99.28%.

Although the absolute increase in availability appears small, even **0.14 percentage points** at system level represents hundreds of MWh of additional energy delivered annually (figure 6).

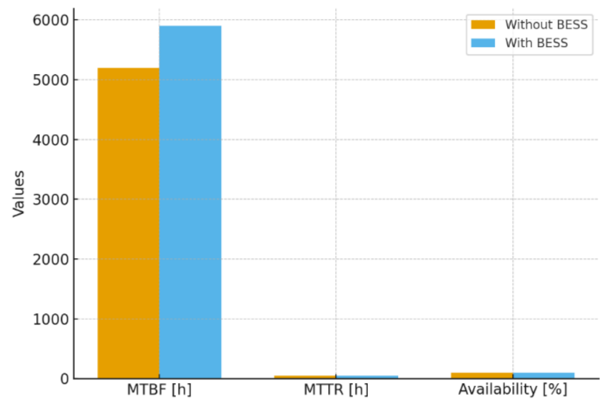

Figure 6. RAM indicators with and without BESS

3.5 Techno-economic evaluation

Based on the methodology (figures 7-8):

- **Cost per unplanned outage:** EUR 20,000–30,000 (including energy not delivered, intervention costs, opportunity costs).
- **Avoided outages per year:** 2–3.
- **Annual savings:** EUR 50,000–90,000.
- **CAPEX:** 2 MW / 4 MWh $LiFePO_4$ BESS ≈ EUR 2.3 million.
- **OPEX:** ≈1.2% CAPEX/year.
- **Payback period (PP):**

$$P = \frac{CAPEX}{Annual\ Savings} \approx 5 - 6 \text{ years} \tag{7}$$

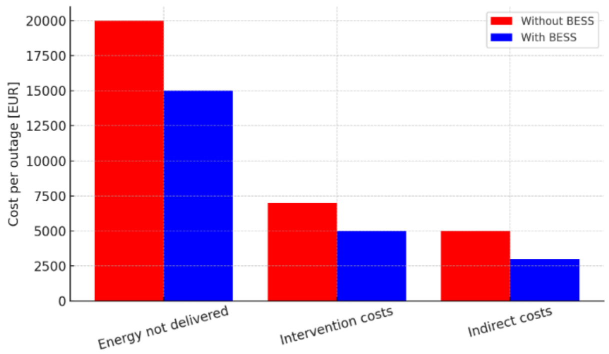

Figure 7. Comparative costs with and without BESS

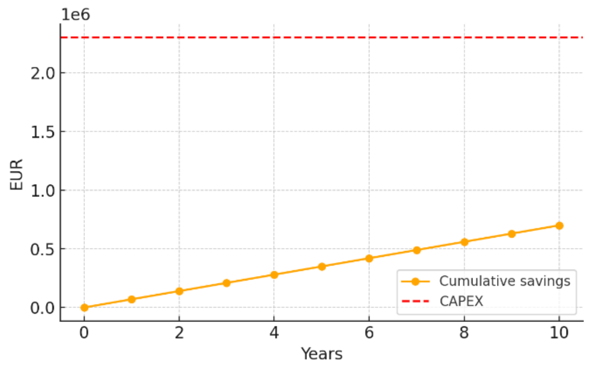

Figure 8. Payback period curve

3.6 Comparative analysis with international projects

- **Norway (Statkraft):** BESS-hydro integration reduced turbine wear by ~20% and improved frequency regulation (ARENA, 2021).
- **Canada (Hydro-Québec):** integration of BESS in small hydro stations increased availability by 0.4% annually (Lazatd, 2021).
- **Australia (Lake Bonney):** hybrid hydro-battery plants achieved additional revenues from fast frequency response markets, improving payback feasibility (IRENA, 2017).

The Drăgan–Iad case study aligns with these results, confirming that BESS is a viable solution for reducing wear and improving the economic sustainability of hydropower plants in grids with high renewable penetration.

4. CONCLUSIONS

This study investigated the operational challenges of the Drăgan–Iad Hydropower Development (Romania), with a focus on reliability, availability, and maintainability (RAM) indicators, vibration and cavitation phenomena during start-up, and the potential benefits of integrating Battery Energy Storage Systems (BESS).

Key conclusions:

- Operational stresses at start-up: HA2 from CHE Remeți faced excessive transient stresses, with RMS vibration levels exceeding ISO 20816-5 limits and ultrasonic cavitation signals surpassing 30 dBμV.
- RAM performance degradation: Frequent start-ups reduced MTBF and availability, with HA2 showing the lowest performance (MTBF = 1048 h, Ao = 88.2%).
- Mitigation with BESS: RMS vibration peaks reduced by ~28%; cavitation intensity reduced by 25–30%; MTBF increased by 13–15%; availability improved by 0.14 percentage points.
- Economic feasibility: Outage cost: EUR 20,000–30,000/event; avoided outages: 2–3/year → annual savings EUR 50,000–90,000; CAPEX: ~EUR 2.3 million; payback: 5–6 years.
- Comparative validation: Results are consistent with international experiences (Norway, Canada, Australia), confirming BESS as a viable solution for hybridization with hydropower plants.

The originality of this research lies in the fact that it is the first applied evaluation on a Romanian hydropower plant (AHE Drăgan–Iad) regarding BESS integration for reducing mechanical stresses, improving RAM reliability, and mitigating cavitation. The results demonstrate the immediate applicability of this concept to hydropower modernization both nationally and internationally.

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