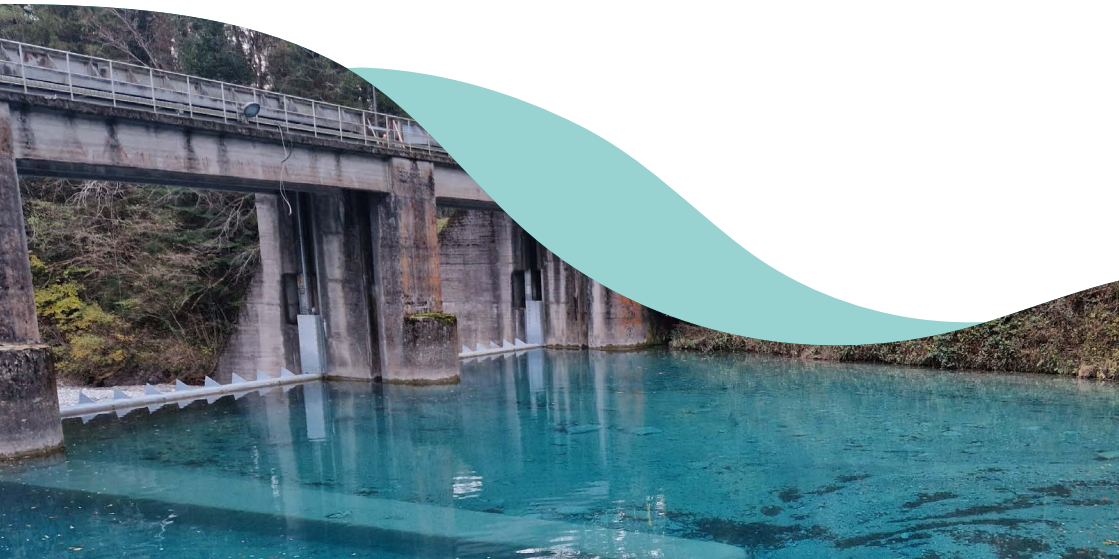
Di-Hydro

DI-HYDRO INNOVATION HANDBOOK

Digital Solutions for Flexible, Sustainable and Resilient Hydropower



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Introduction

- From Ancient Water Wheels to Digital Hydropower
- Purpose of this Handbook
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00

From Ancient Water Wheels to Digital Hydropower

Picture a wooden wheel turning steadily in a stream. No engines or wires—just the force of moving water doing useful work. This principle has supported human development for more than two thousand years. **Water-driven systems were used in ancient civilisations** for grinding grain, aiding irrigation processes, and driving rudimentary machinery. In medieval times, water wheels were used in sawmills and forges, and during the Industrial Revolution, hydropower turbines and generators came to be used.

Despite technological advances, however, the underlying **principles of hydropower generation have remained unchanged**: the energy of moving water is converted into mechanical energy and then into electricity. What has **changed is the environment in which hydropower plants operate**. These now need to adapt to fluctuating energy demand, help integrate additional sources of renewable energy, accommodate aged infrastructure and cope with new hydrological and environmental challenges. And all this has to be achieved while ensuring the safety, reliability, protection of the environment and sustainability of operations.

Furthermore, **many European hydropower plants** have operated for decades. Although their main physical infrastructure often remains robust, their monitoring and control systems may **lack modern sensing, data-processing and artificial-intelligence technologies**. Data may be incomplete, stored in non-digital formats or collected only through periodic inspections. As a result, **maintenance can remain reactive**.

Digitalisation offers an opportunity to address these limitations. Smart sensors, artificial intelligence (AI), forecasting models, digital twins (DTs) and robotic systems can facilitate the monitoring of machinery, physical infrastructure and environmental conditions. These tools could also assist in detecting anomalies, predicting failures, simulating operational scenarios and inspecting locations that would normally put human personnel at considerable risk. These **technologies** do not replace hydropower infrastructure or professional expertise. Rather, they **enhance the ability** of operators and engineers **to analyse the state of plants**, detect potential issues and take action.

This is the objective of **Di-Hydro**, a European research and innovation project supporting the digital transformation of hydropower. The project brings **together plant operators, researchers, engineers and technology developers to design, integrate and demonstrate digital solutions in operational hydropower** environments. Di-Hydro addresses interconnected aspects including environmental and biodiversity monitoring, hydrological forecasting, digital twins, predictive maintenance, structural-health monitoring, cybersecurity, data exchange, advanced visualisation and robotic inspection. In adopting such a field-based approach, the project considers not just the capabilities of the technologies involved, but what it takes for them to be implemented within a real operational environment.

Purpose of this Handbook

This handbook reflects **know-how gained in Di-Hydro** on the practical level in relation to hydropower. It is intended for operators, asset owners, technical staff, environmental experts, technology suppliers, researchers and organisations interested in applying digital technologies in hydropower production.

This handbook does not treat digitalisation as a single technology but **provides insights** into an array of solutions. Every chapter begins with a problem that prompted the application of the technology in question. Thus, the handbook not only describes technological successes but also the practical aspects that affect the use of these technologies.
The purpose of the document is not to offer any one-size-fits-all solution suitable for all power stations generating electricity using hydro-energy. There are differences in the age of the plants, their capacities, configurations, environment, and the computerised technology they already use. Rather, the handbook will provide examples, lessons learnt, and suggestions which can help in making informed decisions on how to adapt to different conditions.

The individual solutions are presented according to a common structure:

- **The Challenge & The Solution**, explaining the operational problem and the proposed response;
- **What Makes It Innovative**, identifying the elements that distinguish the solution from conventional approaches;
- **Real-World Value**, describing the intended users, benefits and observed or expected impacts;
- **Path to Deployment**, reporting validation activities, technological maturity and the steps required for operational adoption;
- **Lessons learnt & Recommendations**, highlighting implementation barriers, practical experience and guidance for replication.

Structure of the Handbook

The handbook is organised into thematic chapters covering the principal areas of digital innovation addressed within Di-Hydro.

Environmental and biodiversity monitoring examines technologies for faster and more continuous observation of water quality, microorganisms and environmental conditions. These include digital holographic microscopy, integrated biosensors, field calibration procedures and biofouling-prevention systems.

Digital twins and simulation technologies present models that reproduce hydrological, mechanical, electrical and control-system behaviour. These tools support forecasting, scenario analysis, plant–grid interaction studies and the evaluation of operational strategies.

Predictive maintenance, structural health and infrastructure monitoring focus on the use of sensors, Machine Learning models and robotic systems to identify equipment degradation, inspect difficult-to-access assets and support proactive maintenance decisions.

Forecasting, hydrology and operational optimisation focus on tools and models for predicting water inflow, organising hydrological data and guiding plant operation. These technologies support decision-support frameworks, inflow forecasting tools and operational requirements for efficient hydropower management.

Cybersecurity, data exchange and IoT systems examine digital infrastructures that ensure safe, interoperable and context-aware hydropower operations. These solutions encompass context-aware IoT models, federated data-sharing architectures and trust-driven security protocols for distributed infrastructure.

Advanced visualisation, AR and field innovations highlight tools that improve asset inspection, plant monitoring and human–machine interaction. These technologies feature advanced visualisation interfaces and augmented reality applications to streamline field operations and interactive maintenance.

01

Environmental & Biodiversity Monitoring

Focus on environmental assessment, sensors, impacts, and ecological forecasting.

- Biodiversity monitoring with the Digital Holographic Microscope
- Integrated Sensoring for Environmental Monitoring
- Field deployment and calibration of environmental sensors
- Biofouling prevention system using ultrasonic system

Biodiversity Monitoring with the Digital Holographic Microscope

The Challenge & The Solution

Understanding the environmental health of a hydropower plant reservoir is crucial, but traditional biodiversity monitoring is often a bottleneck. Standard procedures usually require collecting water samples, transporting them to off-site laboratories, and waiting days for manual microscopic analysis. By the time operators receive the results, environmental issues (e.g. toxic algae blooms) may have escalated.

To address this, AIMEN developed the **Digital Holographic Microscope (DHM)**, an automated, portable system that captures digital holograms from water samples. By processing the phase and amplitude of information from holograms, the system identifies key microorganism species present in the water, such as cyanobacteria, diatoms, and *Anabaena*.

What Makes It Innovative

The primary advantage of the DHM is the ability to bring laboratory-grade analysis directly to the field. Instead of waiting days for results, the DHM provides an assessment of key microorganisms in a few minutes.

While the DHM may not be as precise as a full laboratory setup, it is a relatively low-cost, transportable solution. This allows operators to run tests at multiple key environmental spots across a site, generating a comprehensive and immediate picture of the ecosystem's biodiversity state.

Real-World Value

The DHM is designed for dam operators and environmental agencies. By providing a faster and more accurate picture of reservoir water quality, the tool supports critical, time-sensitive decisions. For example, if the DHM detects a rapid multiplication of cyanobacteria, operators can immediately initiate water oxygenation protocols to halt the algae bloom before it creates a toxic environment.

Key Impact

The implementation of this technology reduces the time required for water analysis from days to mere minutes. Moreover, the DHM supports compliance with EU regulations regarding water contamination and reuse (e.g.; Directive (EU) 2024/3019 of the European Parliament and of the Council of 27 November 2024 concerning urban wastewater treatment).

Path to Deployment

The DHM is currently at **Technological Readiness Level (TRL) 5-6**. To validate its real-world efficacy, the prototype is actively being deployed and was tested at the Međuvršje Hydropower Plant in Serbia.

Parallel laboratory testing has been conducted to improve the tool's accuracy and reliability. However, field conditions are considerably more variable than controlled laboratory conditions, resulting in differences in data quality and performance.

Therefore, **automated identification should be trained and validated using representative field data** rather than relying solely on laboratory datasets.

Lesson Learnt & Recommendations

Lesson Learnt

Translating complex laboratory technology into a field-ready device requires strategic compromises.

During development, the team faced challenges in achieving the exact same image resolution in the portable device as in the lab setup. Consequently, the final design of the first version was simplified due to the limited computing power available in a portable format.

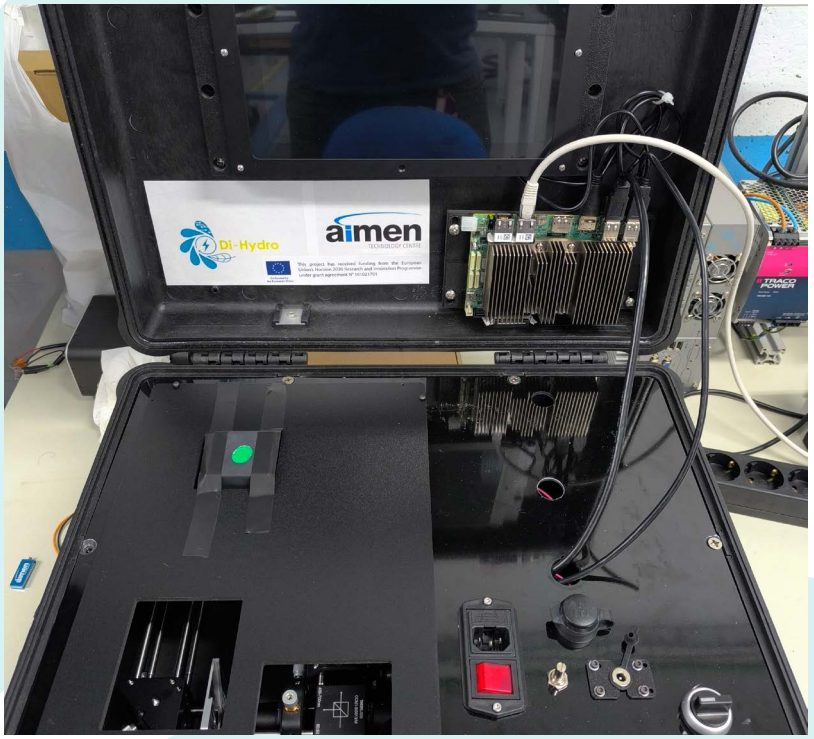

Figure 1: Digital Holographic Microscope

Recommendation

When deploying field-based digital analysis tools, operators should prioritize speed and portability for early-warning detection, utilizing traditional lab tests only as secondary verification when highly granular precision is required.

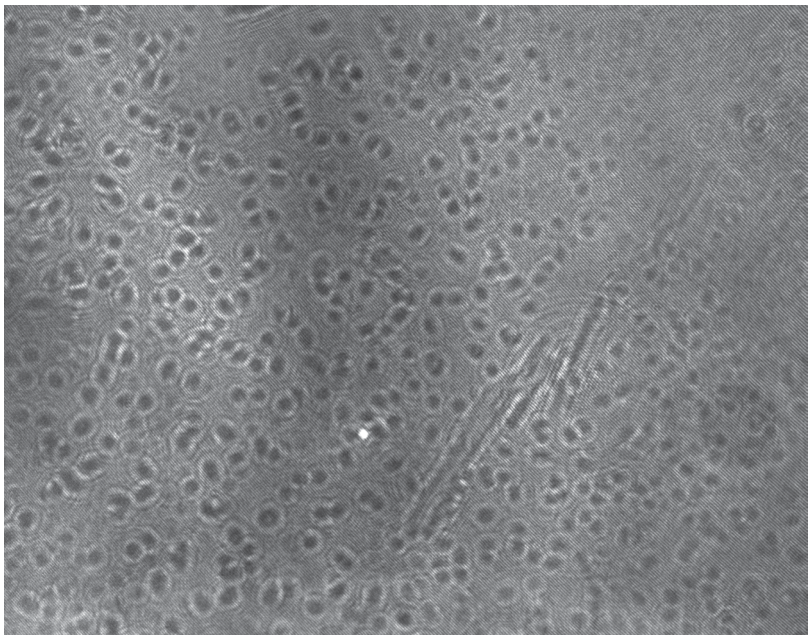

Figure 2: Sample hologram captured by the DHM with Cyanobacteria and Diatomea

Integrated Sensoring for Environmental Monitoring

INOSENS

The Challenge & The Solution

Effective environmental monitoring in hydropower reservoirs has traditionally relied on two extremes: expensive, real-time commercial probes for basic physical parameters or infrequent, manual laboratory analysis for complex biological indicators. This gap means that critical microbiological threats, such as total coliform and *E. coli* contamination or sudden nutrient spikes like ammonia, are often detected only after they have impacted the local ecosystem.

To bridge this gap, INOSENS has developed a unified, real-time sensing system specifically tailored for hydropower environments. The solution integrates specialised electrochemical biosensors (detecting ammonia and *E. coli*) and fluorescence-based sensors (monitoring chlorophyll-a) with conventional probes for pH, turbidity, temperature, and conductivity. This creates a continuous, *in-situ* assessment tool that detects both biological and physical shifts simultaneously.

What Makes It Innovative

The core innovation lies in the transition from "bulky and manual" to "affordable and automated." Unlike typical commercial setups that require high-cost instrumentation or specialized off-site labs, this system utilizes affordable biosensing technology to collect real-time data on microbiological indicators.

By integrating these newly developed sensors into a single, unified stream, the system provides a holistic view of the water's biological health, moving beyond simple temperature or flow measurements.

Real-World Value

This integrated sensing system is a vital tool for HPP dam operators and local environmental authorities. Providing a continuous data stream enables proactive environmental monitoring and management. For example, the early detection of rising chlorophyll, ammonia or E. coli levels allows operators to identify upstream contamination sources or adjust water discharge patterns to protect downstream water quality.

Key Impact

The implementation of this real-time system reduces reliance on costly external lab testing and provides immediate visibility into environmental compliance, facilitating faster response times to ecological threats.

Path to Deployment

The sensing technology is currently at **Technology Readiness Level (TRL) 5**. The system is designed for direct deployment at hydropower facilities, providing continuous water-quality monitoring and functioning as a localised early-warning system.

Cross-validation of the sensor measurements against standard laboratory methods has been completed, confirming the **capability of the system to reliably monitor the selected water-quality parameters** under relevant HPP operational conditions.

The system is now **ready for scale-up and wider deployment**, as well as for extending its application to other environmental and water-quality monitoring scenarios.

Lesson Learnt & Recommendations

Lesson Learnt

Hydropower environments are harsh for sensitive electronics. A key technical lesson was that biofouling and biofilm formation due to the growth of microorganisms on the sensors significantly impacts long-term stability. Without specific protection, sensor accuracy can drift quickly in continuous underwater use.

Recommendation

Organisations planning to adopt similar in-situ sensors should prioritize modular designs that allow for easy calibration and maintenance access.

Incorporating specific biofouling protection and a schedule for periodic cleaning is essential for maintaining reliable, continuous data.

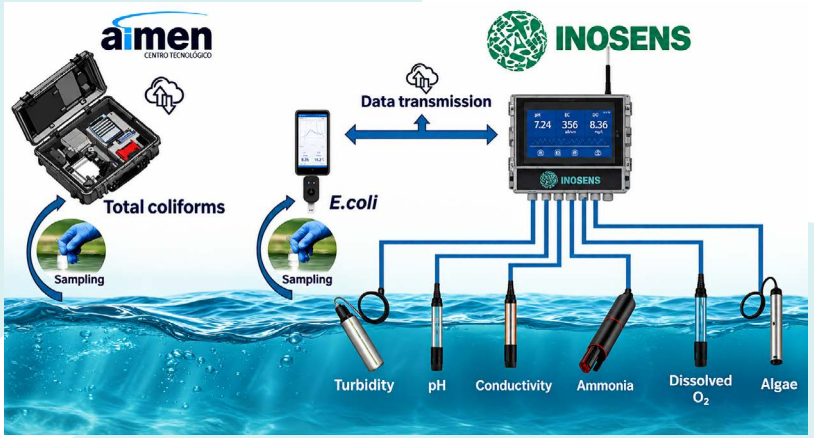

Figure 3: Set of Environmental Sensors

Real-time monitoring data from the novel sensing devices developed WP2

- Water temperature, EC pH
- Dissolved oxygen
- Total coliforms
- Turbidity
- Concontrations of Cyanobacteria (blue-green algee), ammonia, and Escherichia coli

In-situ sampling data through periodical studies of the environmental impact of HPP

- Total coliforms
- Heavy metals
- Microelements
- Biodiversitel parameteres, sediments, etc.

Remote sensing techniques

- Water flow
- Dam opening
- Turbine operation time series
- Impoundment and discharge

MODELS

- Impact of HPP on ecosystem
- Correlation between HPP operation and water quality change
- Predictive models (e.g., ML/AI)
- Evaluation of seasonal and temporal patterns

Visualisation & Reporting

Recommendation for maintenance and operation of HPP

Hydropower plant parameters

- Water flow
- Dam opening
- Turbine operation time series
- Impoundment and discharge

Field Deployment and Calibration of Environmental Sensors

INOSENS

The Challenge & The Solution

Deploying **environmental sensors** in hydropower environments presents significant challenges. These settings expose equipment to dynamic conditions (i.e., fluctuating water flow, temperature, turbidity) which can directly impact measurement stability.

To overcome these barriers, INOSENS demonstrated the integrated field deployment and calibration of a multi-parameter environmental sensing system directly at a hydropower site.

This solution combines both biosensors and conventional probes within a **single monitoring platform** to support continuous *in-situ* measurements and on-site calibration under real environmental conditions.

What Makes It Innovative

Unlike typical approaches that rely on periodic sampling and laboratory calibration, this technological innovation allows for an **integrated platform that continuously measures biological and physicochemical parameters** in water near the hydropower facility.

By utilising specific field calibration procedures and comparison with reference measurements, the system ensures that the sensors maintain accurate and reliable performance during long-term environmental monitoring, **providing actionable environmental data without** the need for frequent **laboratory interventions**.

Real-World Value

The **primary users** of this deployment methodology are **hydropower plant operators**, **environmental monitoring agencies**, and **water resource managers**.

For these stakeholders, this best practice enables them to perform on-site calibration, maintain sensor accuracy, and make timely decisions regarding water quality management and infrastructure maintenance.

Key Impact

Utilising standardised field procedures results in **reduced calibration time** on-site, enabling **more efficient sensor maintenance**. It also guarantees **continuous, reliable data acquisition** over weeks of operation, demonstrating improved sensor stability and resilience under real hydropower conditions.

Path to Deployment

This deployment process was **applied and tested at the Di-Hydro Use Case site Medjuvrsje, in Serbia**, where the platform was installed directly at the hydropower dam to monitor water quality in real operational conditions.

Prior to field deployment, laboratory experiments included sensor calibration with standard solutions, repeatability and selectivity testing, stability tests under controlled variations, and the verification of biosensor response to target analytes.

Based on the completed laboratory and field activities, the deployment approach has been formalised and is **ready for replication and adaptation** to other monitoring sites.

Lesson Learnt & Recommendations

Lesson Learnt

One key lesson learnt is that real hydropower environments expose sensors to dynamic conditions which can impact measurement stability, making robust design and field calibration essential for reliable long-term monitoring.

Key deployment challenges included preventing biofouling, maintaining reliable connectivity for continuous data collection, and ensuring secure installation with ease of access.

Recommendation

To avoid common failures when deploying similar sensors, one recommendation is to implement anti-fouling strategies, design sensors for easy on-site maintenance, and perform regular field calibration to ensure accurate and stable measurements under variable hydropower environmental conditions.

Biofouling Prevention System Deployment

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The Challenge & The Solution

Biofouling is the **formation and accumulation of algae** and other **waterborne microorganisms on components** in contact with untreated water. In hydropower plants, it can occur inside water heat exchangers and water pipes, reducing water flow, clogging heat exchanger surfaces, and **reducing** the **overall heat exchange** performance. This issue is normally **treated by frequent maintenance**, which involves dismantling the components and pressure cleaning them.

To address this, Di-Hydro deploys an **ultrasonic biofouling prevention system**. The solution works by **placing piezoelectric transducers** on the dry side of the surface or component to be protected. These transducers **generate high-power ultrasonic waves** at a frequency range of 20–40 kHz. The ultrasonic waves propagate through the material and **generate cavitation bubbles** in the surrounding water. The collapse of these cavitation bubbles **produces shock waves** that damage the cell wall of micro-organisms (e.g., algae) and disrupts their further attachment.

What Makes It Innovative

What makes this approach distinctive is the **shift from reactive, manual cleaning to a proactive prevention mechanism**. Instead of waiting for biofouling to accumulate and then dismantling equipment for pressure cleaning, this technological solution addresses the biological process directly.

By utilising continuous ultrasonic wave propagation from the dry side of the component, it actively damages micro-organism cell walls, preventing biofouling from forming in a completely non-invasive manner.

Real-World Value

The primary user of this system is **hydropower plant operators**, such as the Public Power Corporation (PPC) In Di-Hydro, more specifically, the plant itself. In Di-Hydro, the successful deployment of this system enabled PPC to conduct less frequent maintenance of the heat exchanger.

Antibiofouling performance evaluations have shown that **lower amounts of biofouling occur compared to unprotected conditions**. Even though some biofouling eventually occurs, the **accumulation is at lower levels** and is significantly easier to clean and remove compared to an unprotected component over the same time duration.

Before anti-biofouling system application

After anti-biofouling system application

Figure 4: Before (left) and after (right) biofouling prevention system deployment

Path to Deployment

The biofouling prevention system has been **tested under real operational conditions at PPC's Pournari plant, showing evidence that biofouling can be prevented and the attached microorganisms were easier to be cleaned**.

The system has been specifically deployed on a heat exchanger.

The testing scenario accounts for specific HPP heat exchanger operational conditions, including the surrounding temperature and water condition.

Lesson Learnt & Recommendations

Lesson Learnt

The application of the system has significantly **delayed biofouling formation**.

However, one of the **challenges** is the **installation** of the **probes** on locations that might be difficult to access. The system needs to operate continuously 24/7, meaning the ultrasonic probes require a continuous power supply. Crucially, the probes must be properly installed to ensure optimum performance; improper installation will not prevent biofouling formation.

Recommendation

Plant operators should apply antibiofouling systems directly to the sensitive components where biofouling accumulates.

Furthermore, the biofouling prevention system can be more effective when deployed for simultaneous use with other biofouling mitigation strategies that an HPP may apply.

Figure 5: Bio-fouling probes installation

02

Digital Twins & Simulation Technologies

Focus on models that reproduce hydrological, mechanical, electrical and control-system behaviour.

- DH Hydrological and Forecasting Models
- Di-Hydro HPP Digital Twin Development
- Development of Reduced-Order Modelica-Based Simulation Models for the Greek Hydropower Cluster
- Circular Integration of Advanced Simulation Tools

DH Hydrological and Forecasting Models

WATERJADE
value in every drop

The Challenge & The Solution

Traditionally, hydropower operators have relied on approaches based on **historical data** (such as using the historical mean as a predictor) **to anticipate water inflows**. To overcome the limitations of backward-looking data, a physically-based **hydrological modelling and forecasting operational service** has been deployed.

This solution delivers **both seasonal and short-term inflow forecasting** by **combining meteorological data** (including ground station data and ECMWF SEAS5/ICON-2I weather forecasts), **snow cover satellite images**, and **historical hydropower system data** (such as reservoir volume and turbined flow timeseries).

What Makes It Innovative

This digital and technological innovation distinguishes itself by directly **coupling a physically-based model with Machine Learning algorithms**.

The integration happens in two key ways: First, Machine Learning handles the downscaling and bias correction of temperature seasonal forecasts, which feed into the seasonal inflow forecasting service. Second, an autoregressive model is used for short-term forecasts.

This model assimilates meteorological inputs and hydrological model outputs together with observed inflow data, refining the physically-based forecasts to achieve **enhanced accuracy**.

Real-World Value

For an HPP technician, this system directly **enables better water inflow forecasting**, according to meteorological forecasts and the specific hydrological response of the catchment.

This leads to highly tangible impacts: during the seasonal inflow forecasting service period (from July 2025 to March 2026), the Waterjade inflow forecasts achieved an **average reduction of error of approximately 70%** (overall, considering all the monthly-issued forecasts) compared to the baseline historical mean predictor.

Path to Deployment

The system has reached an operational-ready maturity level following its **demonstration at the A2A Friuli HPPs** (Lumiei, Novarza, and Ambiesta dams).

The seasonal forecasting service is **already operational**, providing seasonal inflow forecasts to A2A every month.

While the short-term inflow forecast service is already operational, its transition to full operational use would depend on the finalisation and activation of an automatic data exchange agreement with A2A.

Lesson Learnt & Recommendations

Lesson Learnt

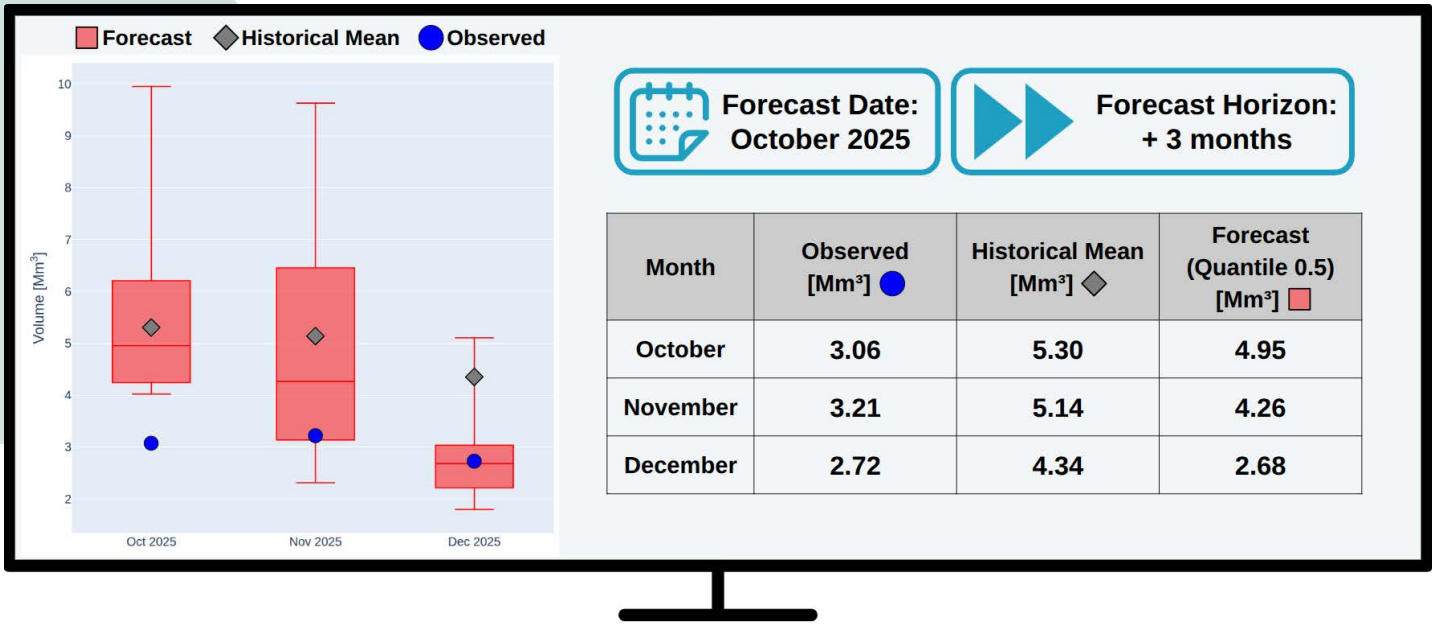
A critical step in setting up inflow forecasting is the careful **identification of main inflow volumes** and the rigorous **calibration of the hydrological model**.

This aims at a more accurate reconstruction of how the hydropower system influences the natural water cycle.

Recommendation

HPP operators implementing inflow forecasting should **prioritise the deployment of physically-based hydrological models** combined with weather forecasts.

Furthermore, **using autoregression** is highly **recommended to achieve accurate and effective short-term inflow forecasts**.



Month	Observed [Mm³]	Historical Mean [Mm³]	Forecast (Quantile 0.5) [Mm³]
October	3.06	5.30	4.95
November	3.21	5.14	4.26
December	2.72	4.34	2.68

Figure 6. Example of seasonal water inflow forecast (+3 months) provided to A2A in one of their points of interest

Di-Hydro HPP Digital Twin Development

ACCELIGENCE

The Challenge & The Solution

Hydropower plants have a very long operational life, often spanning decades. Consequently, **finding** all the **necessary information for modernisation is challenging**, as accurate physics-based simulations require quality input data that is frequently unavailable or exists only in non-digital formats.

To address this, the **Di-Hydro Digital Twin (DT)** has been developed. This solution integrates multi-source data into a **multi-domain, physics-based model that simulates the plant's hydraulic, mechanical, electrical, and control responses** in a synchronised virtual environment.

What Makes It Innovative

While most hydropower digital twins rely primarily on historical data patterns, the **Di-Hydro DT** is distinguished by **its high-fidelity, multi-domain physics-based architecture**. By integrating hydraulic, mechanical, electrical and control systems into a single "sandbox," it **enables proactive, multi-objective optimisation**.

This allows the system to balance peak generation against mechanical fatigue or flood risk, rather than simply reacting to past performance trends.

Real-World Value

The **primary user** of the Di-Hydro DT is the **HPP Operations and Maintenance (O&M) team**. The tool is carefully designed to **bridge the gap between real-time site management and long-term asset strategy**.

For the O&M team, the DT provides the **capability to test long-** and **short-term scenarios** for plant operation before executing them. This empowers operators to perform predictive "what-if" analyses, **transforming raw plant data into actionable strategies** for enhanced energy efficiency and risk management.

Path to Deployment

The core development of the DT was based on the Ilarionas HPP. Moving forward, it will be implemented at this site as a specific DT, and rolled out to other Di-Hydro plants as a generic DT. The initial development phase is complete, and the system is now ready for use in defined operational scenarios.

Validation followed a staged sequence: first, a steady-state analysis confirmed that the model reaches and maintains equilibrium under specified operating conditions, establishing a stable baseline. Then, transient runs exercised time-dependent behaviour such as load changes, valve actuations and control setpoint adjustments. Finally, a final iterative phase was conducted, combining optimisation with validation against historical operating data provided by the plant operator, including deliberate corner-case testing to confirm stability under unusual conditions.

Two results illustrate the outcome: Simulated maximum generated power as a function of hydraulic head (the difference between reservoir level and turbine) correlates with recorded plant data at over 98%. This confirms that this output is properly aligned with real generation behaviour. Simulated generator temperature likewise tracks measured values closely across a three-hour production run; the slight deviation observed during the initial heating phase reflects a difference in measurement basis rather than model error, as Amesim reports a single averaged generator temperature while the plant itself takes readings at several points that differ slightly. Together these results establish the **DT as an accurate physics-driven predictive tool** rather than a purely representational model.

Lesson Learnt & Recommendations

Lesson Learnt

Finding all the necessary information for the development of a DT for **decades-old HPPs is highly challenging**. An accurate physics-based simulation demands **quality input data**, which is often completely unavailable or trapped in non-digital formats.

Lesson Learnt

A multi-domain, physics-based DT is only as useful as the end users' confidence in it. Because O&M decisions carry real safety and financial consequences, the operations team must be able to trust the DT's outputs before acting on them.

To facilitate this, it is useful to Involve the target users (the O&M team) in scenario definition and validation from the outset, rather than treating validation as a final sign-off.

Early and continuous user engagement builds the trust needed for adoption and exposes gaps between the model and real operating practice while they are still cheap to address.

Recommendation

Because the DT is connected to all major subsystems of an HPP, adoption is a complex process.

Development and **adoption** are significantly **easier if executed in stages** instead of an all-at-once approach. Developing, testing, and validating each subsystem individually leads to a substantially faster implementation and adoption process.

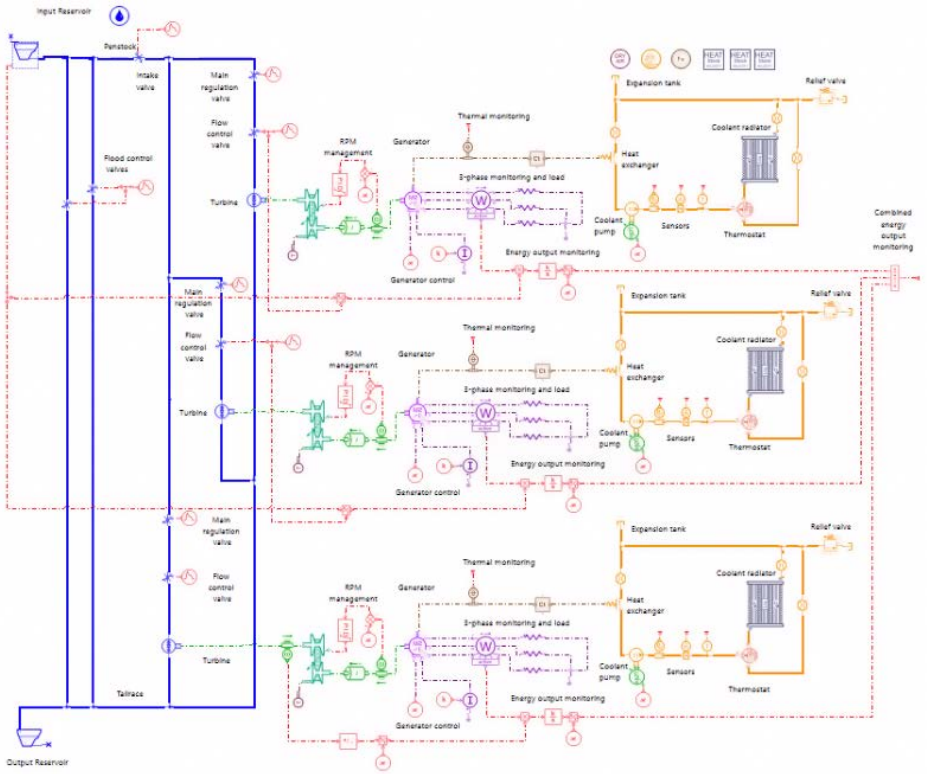


Figure 7. DiHydro DT schematic, comprising of the major hydraulic, electric, power and control systems of the Ilarionas DT

Development of Reduced-Order Modelica-Based Simulation Models for the Greek Hydropower Cluster

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The Challenge & The Solution

Understanding how multiple hydropower units respond to changing electricity demand and frequency disturbances is critical for maintaining grid stability. However, **testing operational scenarios on real infrastructure is risky**.

To resolve this, a **reduced-order Modelica-based dynamic simulation model** was developed to **represent a HPP cluster connected** to a simplified **power grid**. Using the Modelica modelling language, it **translates physical systems into interconnected components** described by mathematical equations.

By employing reduced-order dynamic simulation models, which retain essential dynamic behaviour while reducing variables, the **system** runs **much faster** and remains **computationally manageable** without needing to model every physical detail.

What Makes It Innovative

This digital innovation **balances high fidelity with computational efficiency**. By utilising reusable, block-based components in Modelica, **complex energy systems can be simulated dynamically over time**.

Because it relies on a reduced-order approach, users can perform numerous parameter adjustments efficiently. The model converges quickly, while accurately capturing the key dynamics necessary to analyse system operation, control systems, and primary frequency regulation.

Real-World Value

HPP operators and transmission system operators (TSOs) are the **primary beneficiaries**. The framework provides actionable insights into system operating limits, transient behaviour, and plant–grid interactions. By allowing operators to test control strategies virtually, it **enables** more **reliable grid operation**.

The ability to simulate how coordinated hydropower units can support power dispatch ensures a **better use of hydropower flexibility** for wider power system management.

Path to Deployment

The model was validated using a **cluster of three Greek hydropower plants** (Ilarionas, Pournari, and Thissavros). Using historical power production data, the model was **tested across two scenarios**.

In a 7-day operational simulation, it successfully reproduced the plants' production profiles. In a disturbance scenario featuring a sudden 20% system load increase, the coordinated operation of the three plants reduced the rate of change of frequency (RoCoF) by about 88% and cut recovery time by 40%, **demonstrating the tangible value of hydropower for grid frequency support**.

Lesson Learnt & Recommendations

Lesson Learnt

Dynamic simulation models of hydropower clusters can **effectively reproduce plant operation and system response**, making them invaluable **tools for analysing** coordinated **grid support before implementing** real-world **changes**.

Recommendation

Identifying and calibrating control system parameters (such as exciter gains, PI controller gains, and system inertia) can be highly **challenging**.

Developers should use initial values from literature and refine them through iterative time-domain simulations to achieve stable, realistic dynamics.

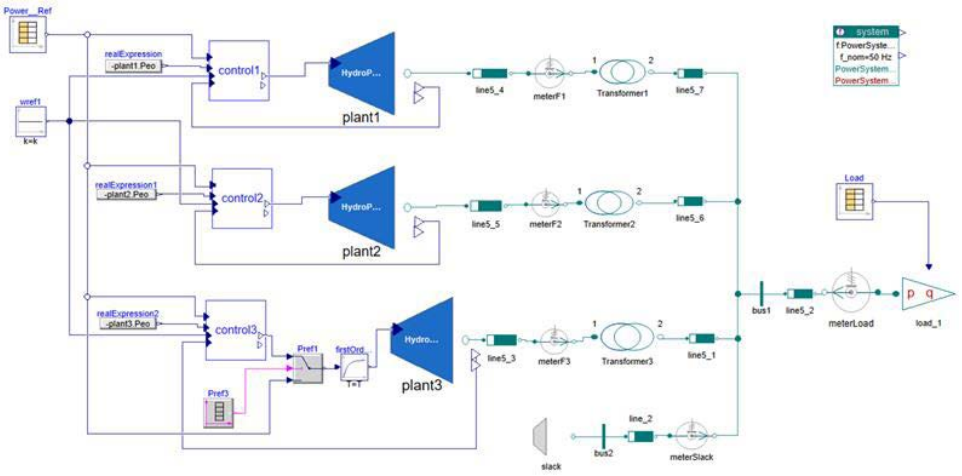

Figure 8. Graphical representation of the model developed in the Dymola UI simulating the load response of 3 HPPs connected to the transmission grid.

Circular Integration of Advanced Simulation Tools

The Challenge & The Solution

Traditionally, hydropower plants treat revenue optimisation, equipment simulation, and maintenance assessment as separate activities. This fragmented approach can lead to operational decisions that maximize short-term profit but inadvertently accelerate equipment wear.

To address this, a digital solution has been developed to integrate a hydropower plant revenue optimisation system with a Digital Twin and a Predictive Maintenance algorithm.

This creates a connected, circular workflow where operational decisions are continuously evaluated not only for their economic return but also for their direct impact on machine behaviour and component health.

What Makes It Innovative

What is distinct and groundbreaking about this digital innovation is that it merges these traditionally isolated domains into a single, integrated decision-support chain.

Rather than relying on separate software silos, the system allows operators to evaluate operating strategies simultaneously from both an economic and an asset-health perspective.

This continuous feedback loop ensures that power schedules can be dynamically adjusted based on real-time machinery conditions, enabling far more balanced and informed operational decisions than typical HPP setups.

Real-World Value

The primary user of this integrated workflow is the trading office. By providing highly accurate information about the actual energy available to be placed on the market, the system enables more informed operational decisions that actively balance revenue maximization with equipment health.

Ultimately, this multi-objective analysis supports both profit maximization and asset preservation, helping to reduce long-term maintenance costs, improve overall reliability, and enhance the plant's operational efficiency.

Path to Deployment

Currently at the concept stage, this integrated chain has been demonstrated at the Greek power plants pilot.

The demonstration scenario involves **using real-time sensor data** from running machines **alongside generated power schedules from the Digital Twin** to estimate plant health.

If the Predictive Maintenance solution identifies an anomaly or potential failure, it forwards this outcome to the Decision Support System (DSS) along with the calculated downtime needed to investigate and fix the malfunction.

The DSS then uses these predicted stops to compute the optimal production strategy.

Lesson Learnt & Recommendations

Lesson Learnt

Integrating specialized tools creates much richer and more useful decision support because it connects economic optimisation with technical and maintenance insights.

However, it also introduces significant challenges in aligning data, assumptions, and timing across different systems.

Recommendation

Any developer wishing to replicate this integration must focus early on defining clear data flows, interfaces, and output/input compatibility between the different tools.

The overall success of the system depends entirely on the reliable exchange of information across the optimisation, simulation, and maintenance models.

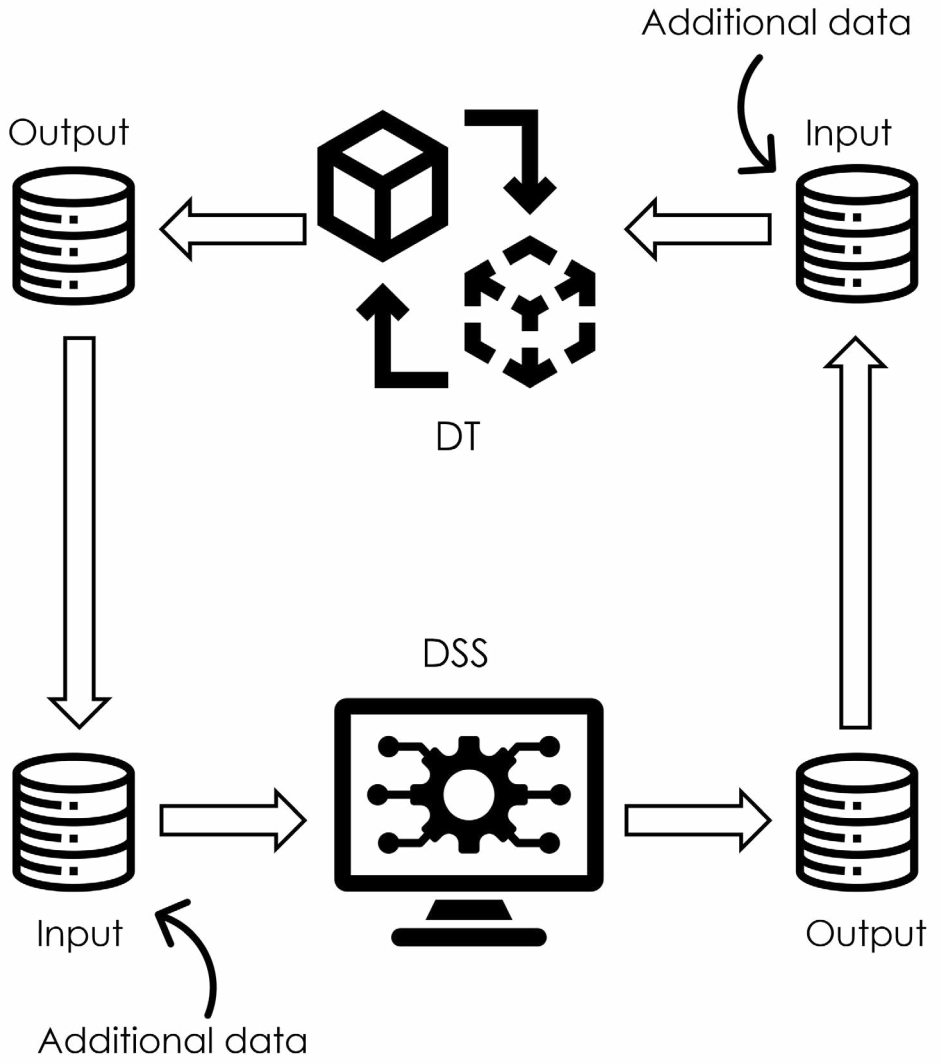

Figure 9: Scheme of the circular integration between the digital twin and the Decision Suport System

03

Predictive Maintenance, Structural Health, and Infrastructure Monitoring

Focus on the use of sensors, Machine Learning models and robotic systems to identify equipment degradation, inspect difficult-to-access assets and support proactive maintenance decisions.

- Predictive Maintenance in Hydropower Plant Equipment
- Fusion Mechanism of PdM Model Results
- Robotic Inspection of Hydropower Plant Water Intake
- Structural Health and Condition Monitoring Sensor Node for Machinery or Infrastructure

Predictive Maintenance in Hydropower Plant Equipment

ATLANTIS ENGINEERING

The Challenge & The Solution

Implementing effective **predictive maintenance strategies in hydropower plants** requires analysis of complex information from various operational components. To address this, a **comprehensive Predictive Maintenance Solution** has been developed.

The solution applies Machine Learning (ML) models designed for **condition monitoring, anomaly detection, and failure prediction**. It operates by being trained on heterogeneous data sources, utilising both historical and real-time inputs.

The data sources comprise SCADA data (e.g., operational turbine time-series), direct sensor measurements, acoustic emissions, vibration data, temperature readings, and other condition-monitoring signals, alongside simulated datasets used for analysis, validation, and model development.

Furthermore, a **fusion mechanism** can combine the outputs of multiple models to deliver more robust and reliable maintenance insights.

What Makes It Innovative

The distinct innovation of this approach lies in its ability to effectively **integrate and process heterogeneous data sources**. Rather than relying solely on standard historical fault logs, the system leverages a blend of simulated data combined with real-world sensor and SCADA inputs.

By incorporating a fusion mechanism to combine the outputs of multiple Machine Learning models, the solution **elevates the accuracy of failure prediction**, offering a highly resilient condition monitoring capability that is more reliable than using standalone models.

Real-World Value

For plant operators, this technology directly **supports and enhances predictive maintenance** strategies within the facility. By reliably identifying anomalies and predicting equipment failures, it enables a **proactive approach to asset management**.

During testing, the ML models were efficiently trained, demonstrating that the system can successfully process **complex data streams to provide actionable, reliable maintenance insights** for critical hydropower machinery.

Path to Deployment

The solution has successfully co**mpleted its training phase and implementation** in the Di-Hydro project.

During the initial training, **simulated data was used from CERTH's lab**, which simulated specific machines of the PPC pilot.

Following this, the **models were parameterised on real data** coming directly from the PPC pilot, utilising actual sensors' and SCADA data.

Having proven that the models can be efficiently trained in this environment, the **next step beyond the Di-Hydro project** may be **further validation and refinement** of the models, using additional operational data to fully support long-term deployment.

Lesson Learnt & Recommendations

Lesson Learnt

When developing predictive maintenance equipment for an existing HPP, the digitalization of the factory is crucial to retrieve data.

Data availability is equally important for training accurate models; ultimately, more data leads to better results.

Recommendation

Any operator planning to adopt predictive maintenance equipment should **invest** early in **data access, sensorisation, and historical data collection**, because model quality and outcome accuracy improves significantly with larger and quality datasets.

Figure 10: Visualisation of the data facilitating the investigation of patterns

Fusion Mechanism of PdM Model Results

ATLANTIS ENGINEERING

The Challenge & The Solution

In hydropower plants, no **single AI model performs equally well under all operating conditions**, asset types, fault modes, and data-quality situations.

To address this limitation, in Di-Hydro a **Fusion Mechanism** was developed to **combine the outputs of different AI models into one final outcome**. This approach **leverages complementary model strengths**. For example, one model may detect subtle anomalies in vibration signals, while another captures temporal degradation patterns.

By integrating these different insights, the combined **result is** significantly **more robust, accurate, and reliable** than relying on any single model alone.

What Makes It Innovative

The primary breakthrough is the **strategic combination of supervised classification with unsupervised anomaly detection**.

In the Di-Hydro context, a supervised model (e.g., XGBoost) can be strong at distinguishing among known classes such as a healthy state, faulty bearings, or unbalance. Simultaneously, an unsupervised model (e.g., encoder-decoder) excels at flagging unknown anomalies.

Fusing these models **reduces the risk of false alarms or missed detections**, leading to more consistent and accurate predictive maintenance results than standalone algorithms can provide.

Real-World Value

The **primary user** of this technology is the **asset manager** or **plant operator**. For these decision-makers, the Fusion Mechanism provides a **reliable, holistic health score** for critical machinery instead of generating a flood of conflicting individual model alerts.

This clear, consolidated output enables confident maintenance scheduling and proactive asset management, directly supporting the long-term health of the hydropower facility.

Path to Deployment

The validation process was conducted using both historical datasets and simulated fault scenarios from the Di-Hydro pilots.

Models were deployed locally and all provided data were used for training and inference.

Models were not deployed directly in the pilots' infrastructure due to data availability and limitations.

Lesson Learnt & Recommendations

Lesson Learnt

Fusing complementary AI models delivers more dependable fault detection and failure prediction than relying on a single-model approach, especially under variable operating and sensor conditions.

Combining supervised classification with unsupervised anomaly detection in a fusion mechanism provides a more robust and future-proof predictive maintenance performance.

Recommendation

Developers considering a Fusion Mechanism for predictive maintenance should design the fusion logic so that **supervised fault classification and unsupervised anomaly detection** remain **complementary**.

Furthermore, they must carefully tune parameters (e.g, weighting strength) to balance sensitivity to known faults with responsiveness to unseen anomalies.

Robotic Inspection of Hydropower Plant Water Intake

CERTH
CENTRE FOR RESEARCH & TECHNOLOGY HELLAS

The Challenge & The Solution

To conduct **inspections of the underwater infrastructure** of a hydropower plant, particularly the water intake inside a reservoir, **traditionally relies on diver-based interventions**. However, deploying human divers into these environments introduces significant **safety hazards**, as these underwater zones can be very cold, feature low visibility, and contain shifting debris.

To mitigate these operational risks, an AI-assisted **robotic inspection framework** has been implemented. The system utilises a **Remotely Operated Vehicle (ROV)** equipped with high-definition imaging, advanced underwater image preprocessing algorithms, and Machine Learning models for automatic damage detection to inspect the water intake in the reservoir and **provide real-time images** directly to the user.

Beyond the primary water intake, the ROV is versatile enough to **inspect other critical submerged areas**, including specific sections of the dam or the bottom outlet, safely accessing hazardous zones past the intake that are entirely unsafe for a human diver.

What Makes It Innovative

The main breakthrough of this solution is that the **ROV** completely **removes** the physical **risk for human divers** having to operate in hazardous underwater conditions. It provides a relatively **low-cost, mobile, and non-destructive inspection tool** delivering immediate **visual data**.

The technology is **specifically geared to automatically identify underwater degradation by improving image quality under difficult underwater conditions**, aiming to detect damage and corrosion of the intake, locate cracks in the concrete sections, and identify pitting of the concrete structure around the water intake areas.

Real-World Value

The **primary users** of this technology are **hydropower plant operators**. In Di-Hydro, this system enables our partner plant operator PPC to know the condition of submerged areas and promptly request targeted maintenance to be carried out. During field validation, the system delivered clear, qualitative indicators of its efficacy by successfully **detecting debris and corrosion** on the water intake, alongside **identifying pitting** on the concrete structures.

Path to Deployment

This technological solution is currently **classified as a mature commercial system**.

Its real-world performance was **verified and demonstrated across two distinct pilot sites**: the Ilarionas HPP (focusing on the water intake scenario) and the Thissavros HPP (where both the water intakes and sections of the dam body were inspected).

To fully integrate this approach into standard asset management processes, these robotic routines will be adopted as part of their permanent asset maintenance scheduling.

Lesson Learnt & Recommendations

Lesson Learnt

Operating an ROV around water intakes presents distinct environmental challenges. The underwater surroundings can be difficult because the tether of the ROV can easily become tangled on submerged rocks or foreign objects.

Additionally, certain areas close to dams can feature excessive water fauna, which can cause direct operational problems to the propellers of the ROV.

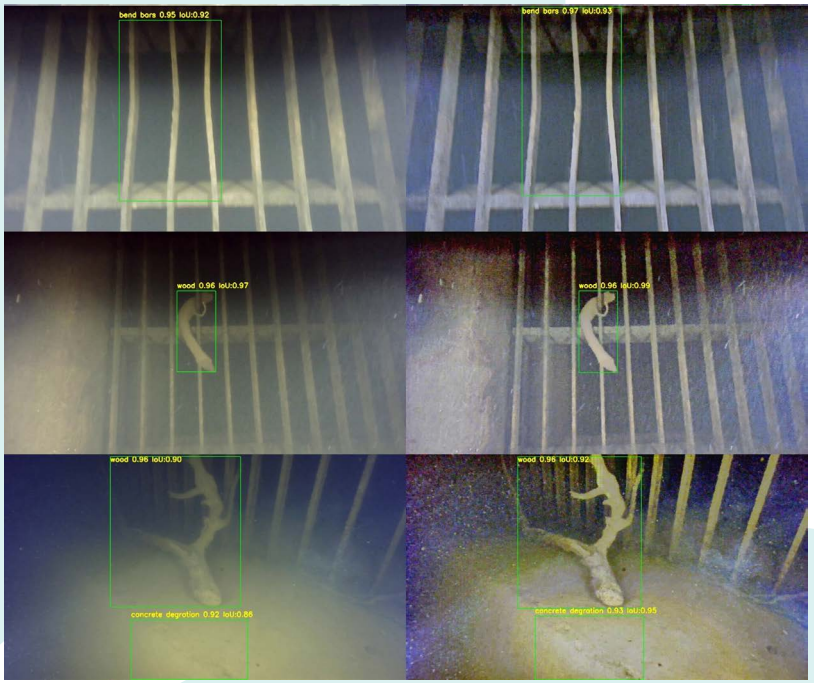

Figure 11: Image and AI-based detection of debris from ROV inspection

Recommendation

Other plant operators should consider adopting similar robotic inspection methods as they represent a highly useful, relatively low-cost tool that effectively eliminates human risk from hazardous underwater maintenance routines.

Figure 12: BlueROV2 (used in DH underwater robotic inspection)

Structural Health and Condition Monitoring Sensor Node for Machinery or Infrastructure

CERTH
CENTRE FOR RESEARCH & TECHNOLOGY HELLAS

The Challenge & The Solution

While primary plant equipment often features modern sensors, critical secondary structures and machinery (such as drainage pumps) are frequently left unmonitored.

Standard commercial units are expensive and require complex hard-wiring into existing plant architectures. To address this, CERTH developed a **low-cost, low-energy mobile Structural Health Monitoring (SHM) sensor node**.

Designed to be **easily retrofitted to various machinery** to monitor damage evolution, the node integrates an **Acoustic Emission (AE) sensor, a microelectromechanical system (MEMS)** comprising a triaxial accelerometer, **gyroscope**, and **magnetometer**, alongside **temperature** and **crack growth sensors**.

What Makes It Innovative

The primary innovation is the **transition from static, expensive hardware** to a highly **comprehensive, retrofittable package**. The AE sensor detects ultrasonic waves generated during cracking or from machinery defects like faulty bearings, gears, and a lack of lubrication. Simultaneously, the accelerometer measures vibrations from shaft misalignments, while the crack growth sensor monitors structural displacement caused by excessive loading.

Correlating these streams (i.e., tracking temperature changes beyond manufacturer limits alongside seasonal atmospheric variations) provides a **multi-dimensional view of equipment health** that surpasses traditional vibration sensors.

Real-World Value

The **primary user** are **HPP operators**. By equipping previously unmonitored "analogue" assets with this node, operators gain **continuous digital monitoring without** the financial burden of plant-wide **permanent instrumentation**.

This vital data is processed by ATLANTIS to carry out predictions for potential machinery failures. Ultimately, this delivers proactive warnings, allowing operators to reduce the risk of unexpected failures and shift from reactive repairs to targeted, predictive maintenance.

Path to Deployment

This pilot is **currently being demonstrated at the Ilarionas HPP** in Greece. The sensor node was installed directly on the drainage pumps, with the penstock selected as a second location to test performance on static structures.

Field testing confirmed the node's ability to operate in rugged plant conditions. To date, no signal deviations indicating machinery failure have been identified.

Lesson Learnt & Recommendations

Lesson Learnt

Retrofitting sensors can unexpectedly **interfere** with daily **HPP operations**, as external cabling is often cumbersome. Additionally, to reduce energy consumption, sensors sleep in small intervals, which means equipment operation is missed and potential faults may go undetected.

Furthermore, the absence of faulty operation data from specific machinery hinders algorithm training.

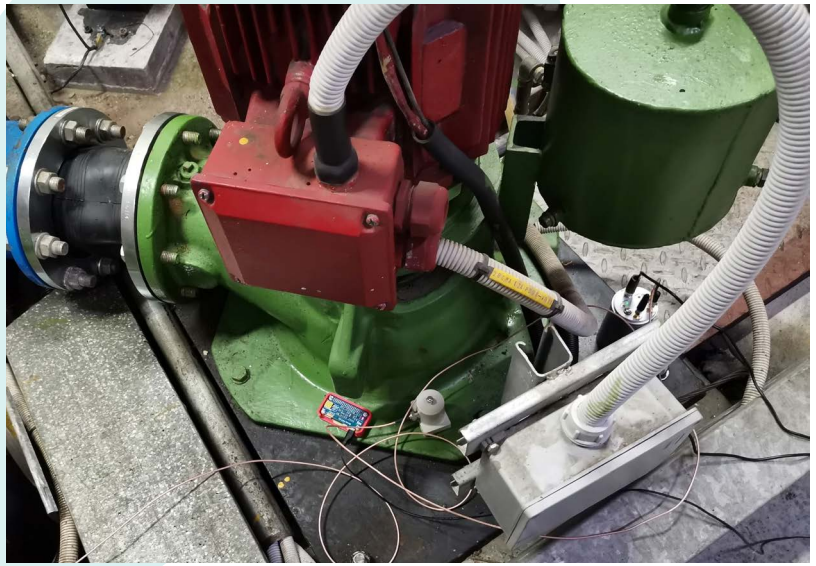

Figure 13. Biofouling probes attached to the turbine's cooling heat exchanger system

Recommendation

Operators must establish **reliable internet and power connectivity**, overcoming remote plant locations, older designs, and strict internal security protocols.

Future installations must improve cable management by integrating sensors and gateways into a single enclosed module with internal cabling and battery options to enable "one-button" operation.

Figure 14. AE acquisition units

04

Forecasting, Hydrology & Operational Optimisation

Focus on tools and models for predicting water inflow, organising hydrological data and guiding plant operation.

- Di-Hydro Hydrological and Forecasting Demonstrative Tool
- IDRO Decision Support System (DSS)

Di-Hydro Hydrological and Forecasting Demonstrative Tool

The Challenge & The Solution

Hydropower operators typically anticipate water inflows using approaches based on historical data, such as historical means. To overcome the limitations of this backward-looking data, a physically-based **hydrological modelling and forecasting service** has been deployed to deliver seasonal and short-term inflow forecasting.

To ensure this complex capability is accessible, a companion demonstrative tool was developed. This application allows non-expert end users (e.g., hydropower technicians without specialized hydrology backgrounds) to **understand** the logical **processes required to set up the hydrological modelling of a catchment** area and independently **produce seasonal water inflow forecasts**.

What Makes It Innovative

This digital innovation couples a physically-based model with Machine Learning. Machine Learning handles the downscaling and bias correction of temperature seasonal forecasts.

On the user-facing side, the tool replaces complex traditional simulation workflows, which often take a week, with guided processing steps and map visualisation.

This **accessibility reduces the total turnaround time for forecast generation by a factor of 20**, dropping it to an average estimated time of 30 minutes.

Real-World Value

For a hydropower technician, this combined approach enables highly accurate water inflow forecasting according to both meteorological forecasts and the specific hydrological response of the catchment.

The system's impact is substantial: during the seasonal inflow forecasting service period (from July 2025 to March 2026), the Waterjade inflow forecasts achieved an average reduction of error of approximately 30% (overall, considering all the monthly-issued forecasts) compared to the baseline historical mean predictor.

Path to Deployment

The operational-ready forecasting model was demonstrated at the A2A Friuli HPPs (Lumiei, Novarza, and Ambiesta dams). The seasonal forecasting service is fully operational, providing monthly forecasts.

Concurrently, the prototype demonstrative tool has been published via a public web link (dihydro.waterjade.com) and can be used to set up hydrological modelling for any catchment in Europe.

Lesson Learnt & Recommendations

Lesson Learnt

The accurate calibration of the hydrological model is critical to accurately reconstruct the hydropower system's influence on the natural water cycle.

Furthermore, integrating graphical visualizations and map viewers while progressing in the creation of the Digital Twin is essential to make the system understandable for non-expert users.

Recommendation

Operators implementing inflow forecasting should prioritize the deployment of physically-based hydrological models.

When replicating the tool for another basin, developers must provide clear and detailed descriptions of all togglable features, map layers, and processing options.

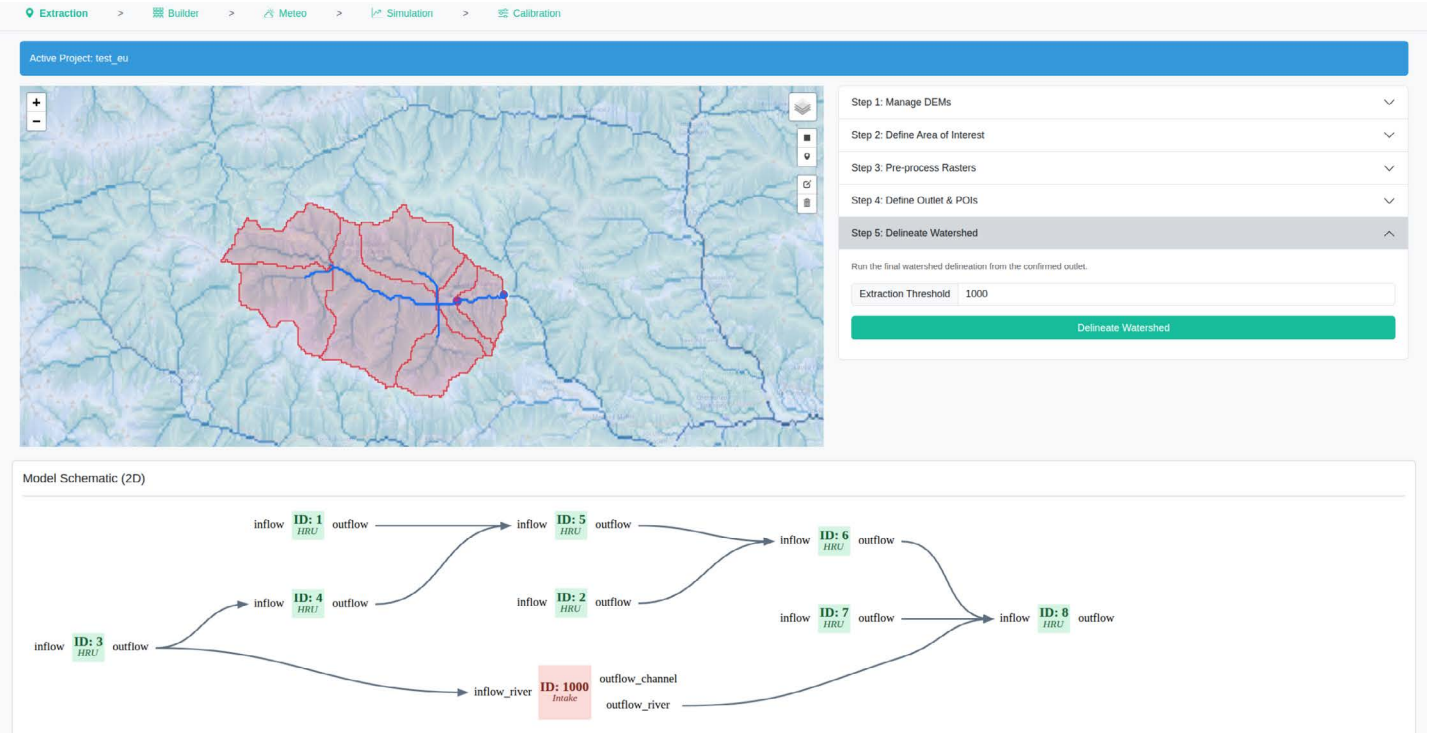

Figure 15. Screenshot of the tool at the end of the geomorphological extraction and the model builder. The graph above shows the connection between HRUs (Hydrological Response Units) and points of interests (anthropic works).

IDRO Decision Support System (DSS)

The Challenge & The Solution

Hydroelectric plant operators must navigate a **complex array of hydraulic conditions and market dynamics** when **planning energy production**.

To maximise the value of energy production and reduce water waste, an advanced **Decision Support System (DSS)** known as the **IDRO platform** has been introduced.

Designed specifically for the **optimisation of hydroelectric plants**, this software employs **advanced simulation** and **planning algorithms** to evaluate both long- and short-term scenarios.

By analysing hydraulic limits alongside market variables, IDRO determines the **most efficient operating strategy**, directly supporting operators in the **optimal management** of their facilities.

What Makes It Innovative

This digital innovation stands out due to its **highly integrated nature**. Traditional decision-making often separates technical management from economic strategy.

The IDRO platform, however, **manages the technical constraints** of reservoirs and power plants **together with exogenous market variables**. By combining hydraulic models, weather forecasts, and energy market trend analysis, the **software** can **optimise the management of extensive hydroelectric systems**, including complex cascades.

By synthesising these diverse data streams, the system automatically **defines the most cost-effective bidding strategy and production schedule** for the energy company.

Real-World Value

Within the Di-Hydro project, the **primary users** of the DSS are the **plant managers and energy traders** from A2A (Italy), EPS (Serbia), and PPC (Greece). For these user groups, the platform ensures that day-to-day operations align with optimal production scheduling.

By delivering clear, data-driven recommendations, the system **enables operators and traders to execute the most profitable bidding strategies** on the energy market, all while strictly **adhering to the physical and environmental constraints** of the infrastructure.

Path to Deployment

To ensure the system meets real-world needs, the requirements collection phase was consolidated through on-site plant visits to **engage directly with partners and local operators**. This engagement context was integrated with software demonstrations and in-depth technical calls, enabling a thorough analysis of every operational detail.

With requirements finalized, the next step is the formal handover to development.

To validate the finalised tool, the platform has been used to **compute a production schedule for a past year**, which has then been directly compared with actual past production data. Operational uptake **included long-term testing, validation, and eventual application to more HPPs**.

The results proposed by the DSS have been tested against both actual historical data results from similar tools already in use by the operators.

The **tool can improve current operations** under the condition that all the constraints and systems are included in the model.

Lesson Learnt & Recommendations

Lesson Learnt

When designing a DSS for industrial energy sites, the most important lesson learnt is **maintaining the careful balance between profound algorithmic complexity and true user-friendliness** for the on-site operators.

Recommendation

To successfully replicate this approach, developers must establish a **continuous flow of technical calls and data exchang**e with their partners. This is crucial to deeply understand their specific operational needs and the intricacies of the plant design.

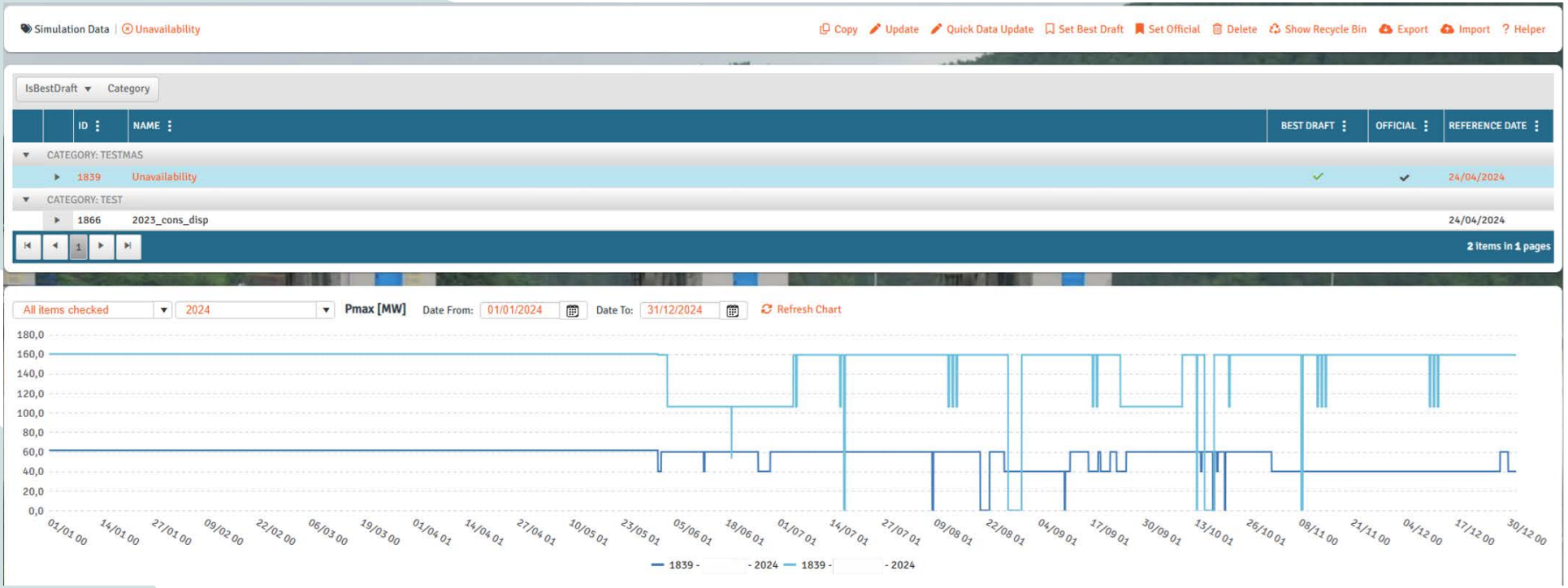

Figure 16. Plot of availability scenario for two HPP in the same Hydraulic profile

05

Cybersecurity, Data Exchange and IoT Systems

Focus on digital infrastructures that ensure safe, interoperable and context-aware hydropower operations.

- IoT-Enhanced Data Models for Context-Aware Hydropower Plants
- Federated Data Exchange Architecture for Real-Time Hydropower Collaboration
- Context-Aware and Trust-Driven Cybersecurity for Distributed HPP Systems

IoT-Enhanced Data Models for Context-Aware Hydropower Plants

Institut Mines-Télécom

The Challenge & The Solution

Typical hydropower data integration relies heavily on proprietary silos or non-semantic formats, making it exceptionally **difficult to link physical infrastructure with modern digital tools**.

To overcome this fragmentation, a **new technological solution utilises NGSI-LD standards to create a modular, semantic knowledge graph**.

This approach harmonises static infrastructure data with dynamic sensor streams and maintenance records. By capturing the contextual dimensions of raw measurements (specifically their spatial, temporal, and device provenance), the **system transforms isolated, raw data points into a cohesive, context-aware network**.

What Makes It Innovative

This digital innovation represents a major breakthrough in **standardising energy infrastructure data**. To the best of current knowledge, this is one of the first domain-specific implementations **of NGSI-LD data models specifically designed for the hydropower sector**.

Instead of forcing data into rigid, localised structures, this semantic framework connects meaning directly to the measurements. It **prevents "brittle and error-prone" automation** by allowing smart applications to receive the information needed to automatically adjust their settings based on semantically structured environmental inputs, rather than relying on hard-coded rules.

Real-World Value

The **primary users** of this development are **maintenance engineers and plant operators**. For these professionals, the semantic knowledge graph **enables highly accurate, data-driven decision-making** by providing a unified view of disparate data sources.

By enhancing interoperability and semantic clarity across the entire data space, operators no longer need to manually reconcile conflicting formats from different equipment vendors. This unified visibility **streamlines daily monitoring** and significantly **improves the reliability of automated plant controls**.

Path to Deployment

The technology is currently at a **lab prototype level** but is continuously being extended and validated. It is part of ongoing deployment and testing across Di-Hydro project sites, with the modeling carefully guided by the physical structures of real pilot facilities.

The **data models** currently **encompass core HPP assets**, including turbines, generators, transformers, and shafts, **as well as specialised monitoring devices** like algae, ammonia, temperature, and RPM sensors.

For further development beyond the scope of Di-Hydro, future steps include the extension of entity types and refinement of model attributes, based on practical validation and feedback from the site deployments.

Lesson Learnt & Recommendations

Lesson Learnt

Effectively mapping heterogeneous legacy industrial data to modern standards **requires specialised IoT Agents** to act as translators between diverse formats and the NGSI-LD standard.

While designing and implementing these agents requires a heavy initial effort, it is necessary to unlock all the long-term advantages of the solution.

Recommendation

Any organisation wanting to replicate this approach must **ensure their models follow open science principles and standard ontologies** (such as SAREF).

This is critical to promote long-term transparency and reusability beyond a single project or facility.

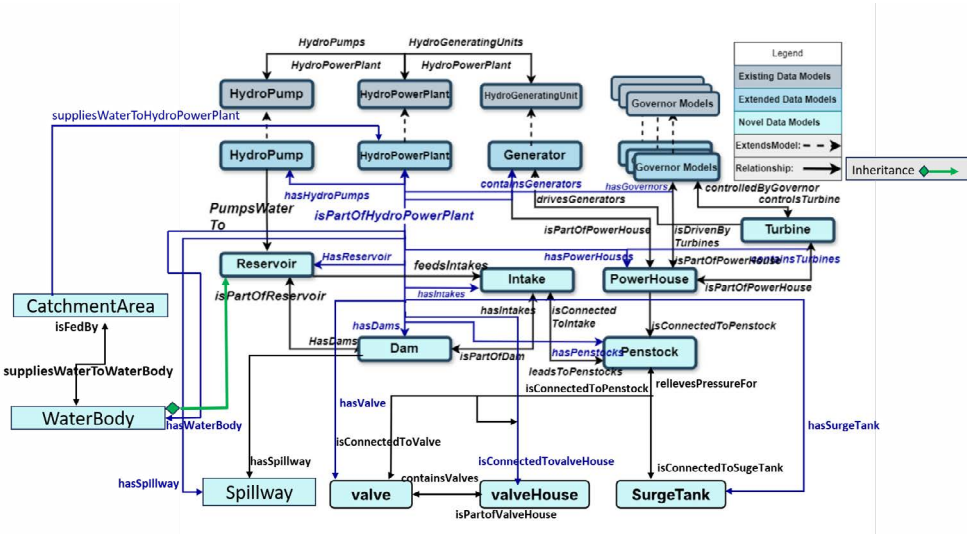

Figure 17. Overview of the Di-Hydro smart ngsi-ld data models for static HPP entities

Federated Data Exchange Architecture for Real-Time Hydropower Collaboration

Institut Mines-Télécom

The Challenge & The Solution

In traditional hydropower operations, cross-site data sharing relies heavily on centralised data hubs or single, all-access central databases. This approach often forces operators to compromise on local data sovereignty.

To resolve this, a new **Federated Data Exchange Architecture** was developed. Unlike traditional centralised data hubs, this architecture **uses a distributed publish/subscribe mechanism**.

This solution **allows for policy-aware, low-latency sharing** while strictly **maintaining local data sovereignty**, enabling semantically harmonised exchange across different stakeholder domains, without relying on a monolithic central database.

What Makes It Innovative

This technological and digital innovation **facilitates** seamless **cross-organisational interoperability**.

By decentralising the data flow and removing technical barriers to selective data routing, it fundamentally **changes how energy partners collaborate**.

Instead of forcing all data into one centralised location, this architecture prioritises **establishing semantic harmony**, ensuring all sites speak the same "data language", allowing systems to interact intelligently and selectively across a distributed network.

Real-World Value

The primary user is any **hydropower plant operator**. For these operators, the federated architecture **enables real-time situational awareness** across multiple distributed sites while ensuring that only authorised, policy-compliant data is shared with external partners.

A key concern users typically have when adopting federated data exchange is the fear that sharing telemetry might lead to a permanent loss of control over sensitive operational insights. This architecture directly mitigates that fear, leading to faster response times to incidents while securely preserving data sovereignty.

Path to Deployment

Currently at a **lab prototype maturity level**, the system has already been used in **cross-partner integration tests**, where data exchanges were successfully carried out between distributed components operated by different consortium partners.

Within Di-Hydro, this represents the final level of validation achieved; any further extension toward dynamic onboarding of third parties or broader operational deployment would be a post-project development opportunity.

Lesson Learnt & Recommendations

Lesson Learnt

Establishing semantic harmony (ensuring all sites speak the exact same "data language") is just as **critical** as the **technical connectivity** itself in order to achieve meaningful collaboration.

Recommendation

Organisations wanting to replicate this architecture must **use standardized metadata and NGSI-LD models** from the start to ensure that the **federated exchange remains scalable** as more sites are added.

Furthermore, to make users more confident in adopting the system, developers should **implement dashboards** that allow operators to visually verify and manage exactly what data is being shared, with whom, and under what conditions.

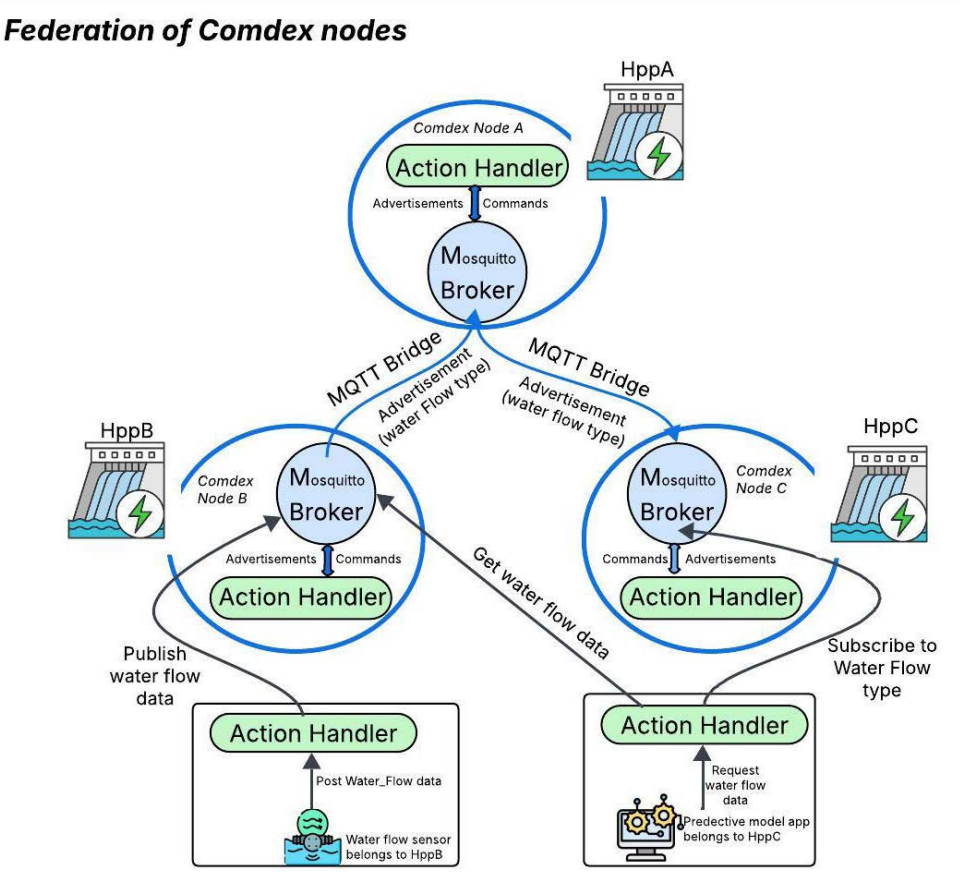

Figure 18. The Di-Hydro federated architecture enabling secure, policy-driven data exchange and semantic interoperability between distributed hydropower plant domains

Context-Aware and Trust-Driven Cybersecurity for Distributed HPP Systems

Institut Mines-Télécom

The Challenge & The Solution

In traditional hydropower infrastructure, cybersecurity often relies heavily on static perimeter security and rule-based firewalls. However, these conventional approaches struggle to protect modern, interconnected facilities from complex threats.

To address this, a Context-Aware and Trust-Driven Cybersecurity system was developed. Unlike static security, this approach uses dynamic trust scores and contextual graphs to evaluate the risk level of actors and devices in real-time.

Using attack-graph risk calculations, the system derives trust values that can support adaptive decisions on whether communication between components should be allowed or restricted.

What Makes It Innovative

This digital and structural innovation represents a novel application of federated, context-aware security specifically tailored for the highly distributed nature of modern hydropower infrastructures.

Rather than relying only on rigid, static rules, the mechanism considers the communication topology, known vulnerabilities and possible multi-step attack paths across the federated environment.

It improves overall system resilience by providing a proactive security layer capable of identifying high-risk components and communication paths that perimeter-based security may not sufficiently address.

Real-World Value

The primary users of this system are OT Security Officers. For these professionals, the technology supports the risk-based restriction or isolation of potentially compromised devices before a cyber-threat can propagate through the hydropower network.

A primary adoption concern in real-world settings is the risk of false positives, where legitimate communication could be restricted because of an inaccurate or incomplete security assessment.

For this reason, the calculated risk and trust results should initially be reviewed by security specialists before active communication restrictions are enabled.

Path to Deployment

Currently at a **lab prototype maturity level**, SHIELD has been implemented and used within Di-Hydro to assess the trustworthiness of devices participating in the project's federated environment, based on their vulnerability exposure and attack-path risk.

It has also been exercised in controlled scenarios to support integrity verification and trust-based communication decisions between project components.

Within Di-Hydro, this demonstrates the practical integration of dynamic trust assessment with the federated data-exchange architecture; broader validation in more diverse operational HPP networks would be a future development step beyond the project.

Lesson Learnt & Recommendations

Lesson Learnt

When applying "dynamic trust" in an industrial setting, the greatest challenge is achieving a balance where security is tight enough to stop threats but flexible enough not to disrupt critical, real-time operations.

Recommendation

Organizations planning to replicate this approach should initially use the system in a passive assessment phase.

This allows security teams to review the calculated risk and trust results and refine the security policies before enabling the active blocking of communication between devices

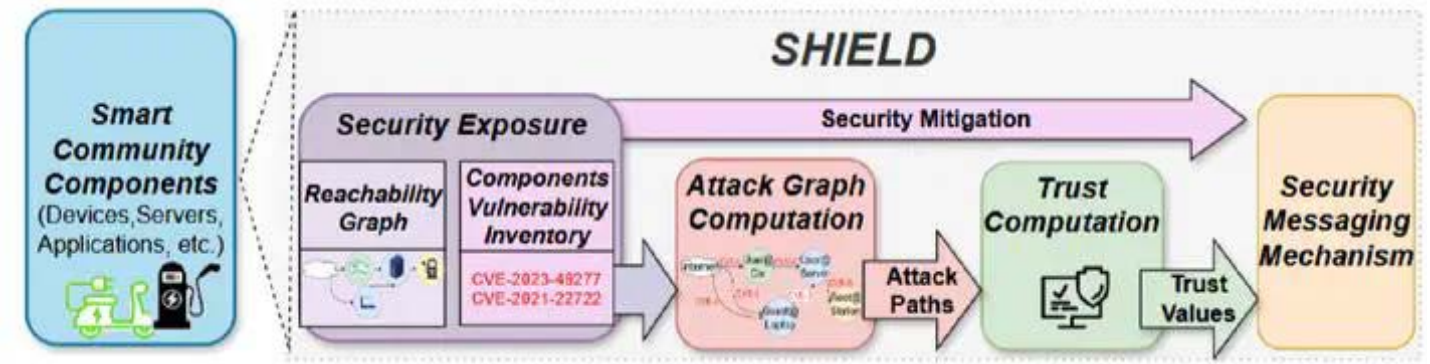

Figure 19. Overview of the SHIELD framework architecture

06

Advanced Visualisation, AR & Field Innovation

Focus on tools that improve asset inspection, plant monitoring and human–machine interaction.

- Di-Hydro Advanced Visualisation Tool
- Di-Hydro Advanced Visualization Tool Pilot Augmented Reality (AR)

Di-Hydro Advanced Visualisation Tool

The Challenge & The Solution

Hydropower plant (HPP) operators must continuously monitor parameter data from heterogeneous sources to maintain safe and efficient operations.

Often, raw data is difficult to interpret quickly during critical moments. To address this, AP2K developed the **Di-Hydro Advanced Visualisation Tool (VT)**. This Graphical User Interface automatically converts raw HPP tags into real parameter names. It **displays current values alongside history values with continuous graphs and predefined alert limits**.

When these limits are surpassed, the VT immediately throws a warning, providing a centralised and highly intuitive overview of the plant's operational status.

What Makes It Innovative

This technological and digital innovation **combines interactive parameter data, real-time graph displays, and alert warning systems into a single interface**.

Furthermore, it **integrates historical analysis with AI-based forecasts**. Specifically, the tool uses an API to collect weather data and run a forecast algorithm for the plant's specific region (such as the Ilarionas zone in Greece).

This integration of predictive weather changes **allows operators to proactively anticipate** the corresponding **changes in water parameters** rather than just reacting to them after the fact.

Real-World Value

The **primary users** of this system are the **HPP operators** stationed in the control room. For the HPP control room operators, this centralised interface **enables the fastest notice of critical values**, ensuring that operational settings can be adjusted as quickly as possible.

By presenting clear, actionable data, it reduces cognitive load and accelerates decision-making during critical events.

Path to Deployment

A **beta version** of the Visualisation Tool is already **complete**. It has been successfully tested locally at AP2K, with no issues encountered regarding the display of the current data.

The system is designed to **work uniformly across any facility**, and the first real-world implementation is demonstrated directly inside PPC's control room on a big screen. Moreover, the MQTT Broker was used to acquire data, resulting in the Visualisation Tool to be fully user-based.

The final phase of the beta version gathers any type of data directly from the users.

In conclusion, there is no need for new data for the visualisation tool. The testing phase was completed, and the data collection is automated for each user.

Lesson Learnt & Recommendations

Lesson Learnt

Developing advanced visualisation software is highly dependent on **timely data access**.

The biggest and only major challenge encountered during this tool's development were delays in data retrieval from the target HPP.

Recommendation

Developers creating control room interfaces must establish **strict data retrieval protocols** and **secure sample datasets** from HPPs at the very beginning of the project to avoid data compatibility bottlenecks.

Figure 20. The Visualisation Tool is a Graphical User Interface designed for HPP operators monitoring of HPP parameter data. The VT contains current values, alerts, warnings, continuous graph display.

Di-Hydro Advanced Visualization Tool Pilot Augmented Reality (AR)

The Challenge & The Solution

In traditional hydropower plants, control room operators often need to physically walk to the equipment to inspect its status, which can delay response times during critical moments. To bridge this physical gap, AP2K developed the **Di-Hydro Advanced Visualisation Tool Pilot Augmented Reality (AR)**.

The AR display monitors both the HPP's parameter data and its hardware via a live camera stream. The user interface design is deliberately minimalist, to allow ease of use by the operator; they can simply see what is important, and there is no need to press any button after running the tool.

What Makes It Innovative

This technological and digital innovation advances beyond standard dashboard visualisation.

What sets the AR Pilot apart from the standard Visualisation Tool is the **integration of the live camera stream of the hardware** components, combined with focused data, displaying only 3 important parameters per section.

By giving a live camera stream of multiple hardware components and parameter values at the same time, it **provides a fast and optimal data monitoring**, bringing the hardware status directly to the operator room without the need to walk to it.

Real-World Value

The **primary users** of this technology are the **HPP control room operators**. For these operators, the AR display enables the **fastest notice of critical values**, so the action of closing or changing operational settings can be as quick as possible, especially regarding the hardware live stream display.

Ultimately, the integration of targeted warnings and the live stream empowers operators to give the fastest response in a critical moment, maximising efficiency and safety.

Path to Deployment

Local **testing is completed and automated** to contain a window where the camera and IP configuration details are inserted by the user.

Similarly to the Visualization Tool, the testing phase was completed with MQTT data. Currently, each user can input IP and camera configuration.

The data loaded by the users is automatically displayed with a layer of camera-stream.

Lesson Learnt & Recommendations

Lesson Learnt

The primary challenges when implementing AR camera integrations in industrial environments are the **physical connection of multiple cameras** for the live stream and securing the necessary security and administrative approval for it.

Recommendation

When designing AR interfaces for control rooms, developers should prioritise a **minimalist layout** that requires no button pressing during operation, ensuring operators receive only the most vital information without cognitive overload.

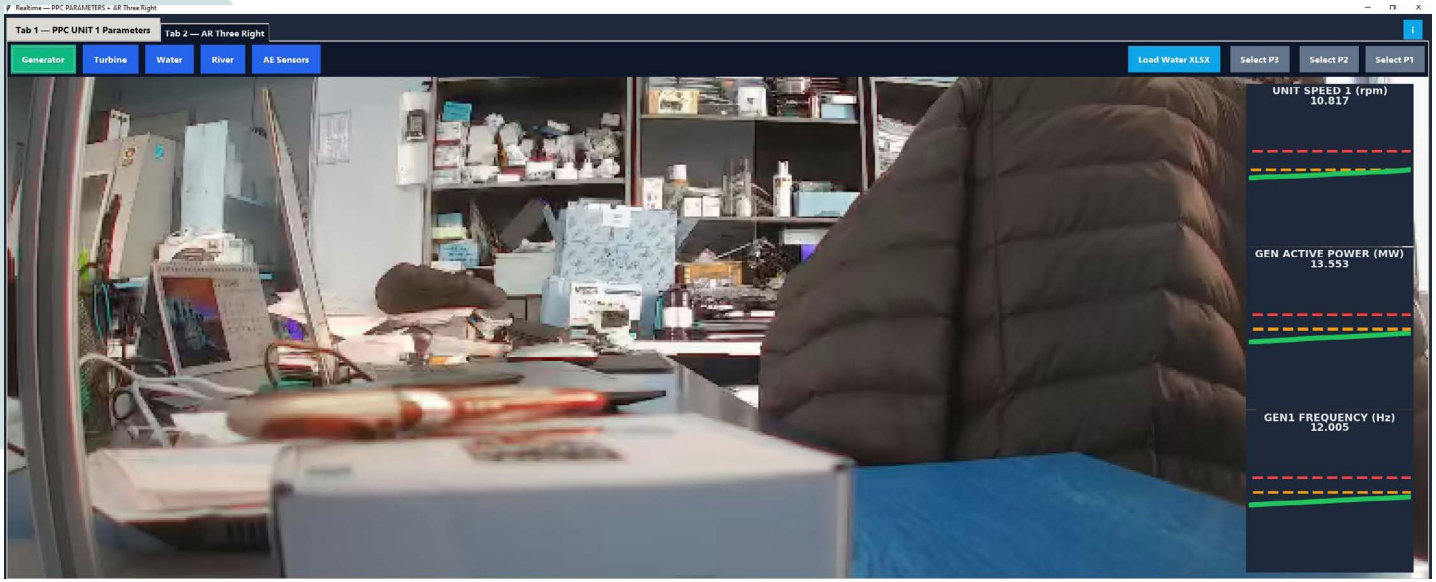

Figure 21. The Di-Hydro Advanced VT AR gives a live camera stream of multiple hardware components and parameter values at the same time, providing the fastest and optimal data monitoring

Conclusions

- From Innovation to Implementation

07

From Innovation to Implementation

Hydropower has evolved over the centuries, using the same basic principle to meet new technical and operational needs: harnessing the movement of water to produce useful power. Early systems used flowing water for mechanical work, while modern hydropower plants generate electricity through turbines, generators, control systems, and large infrastructure. Although this physical principle remains the same, the **role of hydropower** has grown. Today, plants are **expected to do more** than just produce electricity; they must also support flexible energy systems, integrate additional renewable sources, manage ageing infrastructure safely, respond to shifting hydrological and environmental conditions, and uphold high standards of reliability and sustainability.

These expectations necessitate improved **monitoring, forecasting, maintenance planning, data sharing, and decision support**. Di-Hydro directly addresses this need. The project promotes the **digital shift in hydropower** by designing, integrating, and demonstrating technologies for **environmental monitoring, hydrological forecasting, digital twins, predictive maintenance, structural health monitoring, cybersecurity, data exchange, advanced visualisation, and robotic inspection**. Its goal is not to replace existing hydropower infrastructure but to help operators and engineers better understand plant conditions, anticipate risks, and make informed operational decisions. This handbook turns the Di-Hydro experience into practical advice. The handbook offers examples, lessons learnt, and recommendations to assist operators, asset owners, technical staff, environmental specialists, technology providers, and researchers in determining how digital tools can fit different hydropower scenarios.

The solutions developed in Di-Hydro show that **digital hydropower** is best seen as an **interlinked set of capabilities**. Environmental and biodiversity monitoring increases awareness of water quality, microorganisms, reservoir conditions, and biofouling risks. Hydrological forecasting, digital twins, and simulation technologies help improve understanding of plant behaviour and operational scenarios. Predictive maintenance, structural health monitoring, and robotic inspection enhance knowledge of asset conditions and enable safer, more focused maintenance. Forecasting, hydrology, and operational-optimisation tools link data and models to planning and production decisions.

Cybersecurity, data exchange, and IoT systems provide the secure, interconnected infrastructure needed for digital collaboration. Advanced visualisation and augmented-reality tools make complex information easier for operators to use.

Across these areas, one lesson stands out: **digitalisation adds value when it addresses real operational needs**. Sensors, models, algorithms, and interfaces are helpful when they enable people to observe conditions earlier, clarify complexities, anticipate risks, and act with greater confidence. Their value hinges on the quality of the data they use, the dependability of the systems that gather and share that data, and users' ability to understand and apply the resulting information.

The Di-Hydro experience also confirms that **digital technologies must be tested in real-world conditions**. Hydropower settings expose equipment and digital systems to water, humidity, vibrations, turbidity, biofouling, limited connectivity, difficult access, and strict operational constraints. Laboratory testing and prototype development are important, but not enough. Technologies become truly relevant when they can be installed, maintained, interpreted, and utilised within the practical and organisational conditions of real hydropower plants.

Another key lesson is that **individual tools are more valuable when they connect to workflows**. Monitoring can inform modelling; modelling can support prediction; prediction can guide maintenance and planning; visualisation can make results actionable for operators. This requires compatible systems, secure data exchange, and integration with existing plant processes. Digital hydropower should be developed as an ecosystem of interrelated capabilities rather than as a set of separate applications.

The project also highlights the importance of **people, trust, and governance**. Digital systems should simplify tasks for operators, engineers, asset managers, environmental specialists, and cybersecurity teams instead of adding extra burdens. Their outputs must be clear, timely, and actionable. At the same time, increased connectivity makes cybersecurity, access control, data ownership, and governance critical from the start of design and deployment.

Taken together, these lessons suggest a **practical roadmap for digital hydropower**. Plants should begin by identifying operational issues where digital tools can provide real value. Next, they should evaluate the available data, determine the necessary sensing and connectivity requirements, validate technologies in the field, involve users early, integrate tools step by step, and ensure that cybersecurity and data governance are included in the design from the beginning. This step-by-step approach lowers implementation risks and supports more realistic replication across different plants.

Di-Hydro offers tested experiences and implementation lessons to guide informed decisions on how to adapt, combine, and implement digital technologies in real hydropower contexts. This is especially important because plants differ in age, configuration, digital capabilities, environmental conditions, connectivity, maintenance practices, and operational routines.

The shift from traditional hydropower to digital hydropower continues the same engineering principles that have shaped hydropower over time: adjusting the use of water to meet changing needs. In this next stage of evolution, converting water into reliable value is complemented by another conversion: turning data into insight, insight into decisions, and decisions into safer, more sustainable, and resilient operations.

Figure 22: Di-Hydro Consortium at A2A Museum in Milan

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