



## ANNEX to the IEA Hydro TCP Implementing Agreement for

### Task 20:

## Digital Twin of Hydropower 1.0

Application submitted by:  
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### 1 Background

The concept of digital twin (DT) is defined by ISO/IEC 30173:2023 as “a data model that establishes and manages connections between the physical and digital worlds through software and digital technologies,” DT enables real-time monitoring, predictive analytics, and scenario simulation worldwide.

The Strategic Research and Innovation Agenda (SRIA) by the EERA Joint Programme on Hydropower advocates smart operation, predictive maintenance, and DT integration to enhance plant availability. EU-funded initiatives like iAMP-Hydro, D-HYDROFLEX, and Rehydro further underscore this focus, leveraging DT-driven decision support systems (DSS) for vibration analysis, sediment management, and grid optimization. Meanwhile, Gouvães Pumped-Storage Plant in Portugal employs DT for operational optimization, aligning with Europe’s renewable energy transition goals.

In the U.S., the Department of Energy’s Digital Twin for Hydropower Systems – Open Platform Framework (DTHS-OPF), led by Oak Ridge and Pacific Northwest National Laboratories, targets aging infrastructure modernization through modular, data-driven solutions. General Electric’s three-tier “data + models + applications” DT framework exemplifies industry-driven innovation.

China has achieved significant accomplishments in the application of digitalization for large-scale hydropower projects in recent years. The China Three Gorges Corporation, a key player in this field, has developed an intelligent application for the DT of hydraulic turbine generator units. This application delivers intelligent guarantees for the units’ efficient and reliable operation via six core functions: condition monitoring, fault diagnosis, health assessment, digital twin, and digital maintenance.

Additionally, by adopting the combined approach of "high-precision computational fluid dynamics (CFD) simulation model + machine learning", the prediction speed of the flow field in the whole hydraulic turbine flow passage can be increased to the second level—effectively addressing the limitations of traditional CFD simulations in real-time monitoring and abnormal condition diagnosis.

Similarly, the Huangbai River Digital Twin System employs DT to optimize flood management, resource allocation, and infrastructure safety, demonstrating tangible operational efficiencies.

Collectively, these initiatives highlight digital twin technology's pivotal role in advancing smart hydropower systems, driving resilience, sustainability, and cross-sector collaboration worldwide.

## 2 Introduction

Digital Twin (DT) technology has emerged as a transformative solution, enabling virtual representations of physical hydropower units for enhanced performance, predictive maintenance, and decision-making. Based on the earlier questionnaire results and research experience, this research task aims to achieve:

- Visual monitoring: Develop a highly realistic 3D interactive visualization interface that displays real-time parameters and status.
- Prediction and warning: Predict equipment failures and performance degradation, and issue early warnings.
- Operation optimization: Optimize operation strategies to enhance power generation efficiency and other comprehensive benefits.
- Intelligent maintenance: Reduce costs and improve efficiency through intelligent planning and resource scheduling for maintenance.
- Knowledge sharing: Create a platform for direct queries of specific indexes and solutions from past similar incidents.

With the task objectives listed above, four major research topics have been established to fulfill these goals:

- Monitoring and perception of hydropower units and its data collection and management
- Model construction related to the entire process of DTs development for hydropower units
- Building and deployment of DTs for hydropower units and their intelligent application development
- Retrofitting of out-of-date equipment and facilities of aging power stations for DTs deployment

The study on monitoring and perception technology for hydropower units explores advanced technical means that go beyond conventional online monitoring systems. The goal is to achieve more extensive and multi-dimensional perception and collection of both static (e.g., geometric features and physical properties) and dynamic (e.g., pressure, temperature, and flow rate) data of the units, thereby supporting the subsequent building and operation of the DTs of the units. For instance, utilizing IoT-based sensors, vibration analysis, and acoustic emission monitoring, the research assesses real-time mechanical and hydraulic performance of turbines, generators, and other structures. Fiber-optic sensing enables precise strain and temperature detection, while LiDAR and computer vision technologies track surface deformations and sediment accumulation.

The study on data transmission and storage technology for DT systems of hydropower units aims to explore the applicability of the high-speed, low-latency, high-performance, and high-secure data

transmission protocols (e.g., Fibre Channel Protocol and 5G technology) and their corresponding devices, as well as the application of more advanced database technologies (e.g., distributed file storage (DFS), NoSQL database, NewSQL database, and cloud storage) for storing the massive volumes of multi-source heterogeneous data. This study will support the further processing, management, and analysis of DTs data.

The data processing and integration for DT systems of hydropower units aims to perform necessary preprocessing and integration of data from the monitoring and perception system of the units, as well as other relevant systems (e.g., the dispatching system and maintenance management system). This process lays a solid foundation for the development and application of data analysis models. For instance, data cleaning techniques such as outlier detection, noise filtering, and missing-value imputation are employed to ensure high-quality datasets from heterogeneous sensors (e.g., vibration, pressure, and temperature). Meanwhile, various data fusion methods, including random methods and artificial intelligence methods, can be applied to effectively synthesize, filter, correlate, and integrate multi-source data.

The models are crucial components in the building and application of DTs for hydropower units. These models can be categorized into three dimensions: 3D geometric model, physics and behavior models, and rule model. 3D geometric model describes the hydropower unit in terms of its shape, size, tolerance, and structural relation with appropriate data structures, which are suitable for computer information conversion and processing. Additionally, other related information of the key components, such as material information and assembly information, is also included in the geometric model. Physics and behavior models are advanced simulation models built upon the geometric model. Through sophisticated mathematical algorithms and simulation technologies, such as physics-based simulation and data-driven simulation, they predict the responses and changes of hydropower units under different conditions, thereby describing the dynamic behavior and operating status of the hydropower units. Rule model describes the rules extracted from historical data, expert knowledge, and predefined logic. These rules equip DTs with ability to reason, judge, evaluate, optimize, and predict, thus supporting the development of intelligent applications based on DTs.

The building and deployment of DTs for hydropower units aims to integrate, map, visualize, and synchronize various data and models, ultimately completing the construction, validation and application of the DTs. The technologies used include model lightweighting technology, 3D rendering and visualization technology, and scalable architecture design, among others. For instance, Leveraging computer graphics engines and scientific visualization tools, the research develops high-fidelity 3D models that integrate CFD results, structural stress distributions, and real-time sensor data into dynamic visual outputs. Virtual Reality (VR) and Augmented Reality (AR) platforms enable operators to interact with spatially accurate renderings of turbine flows.

Based on the deployed DTs of hydropower units, technical study will be conducted to develop various intelligent application services, such as intelligent warning and diagnosis, health status assessment, and intelligent maintenance, thereby achieving advanced monitoring, diagnosis, prognosis, maintenance, etc. For instance, machine learning-based anomaly detection can identify turbine wear or structural cracks, thereby reducing downtime. Virtual control rooms can simulate emergency responses, providing training without physical risks.

The retrofitting of aging hydropower infrastructure with DT technology enables legacy plants to achieve modern operational efficiency and predictive capabilities through non-invasive IoT sensor deployment, edge-computing gateways, and hybrid physics-AI modeling. By instrumenting vintage turbines with vibration, strain, and hydroacoustic sensors, real-time data is fed into adaptive digital replicas that compensate for missing historical data through transfer learning and machine learning techniques.

The Task 20 aims to address these goals through several types of research topics over the years. The proposed working plan is described in the next section.

### **3 Task manager and participating entities**

The new Task has been initiated by China and supported by other participants.

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### **4 Work plan**

The current section highlights information on what is planned within the proposed Task 20. The proposed plan consists of activities and deliverables presented through the three main phases of the Task: starting – operating – and closing phases. The planned timeframe for Task 20 is expected to set a 3 years and 9 months period from 04.2025 to 12.2028. In addition, the proposed work of Task 20 will align with several priority areas that are set within IEA Hydro as described in Section 5.

#### **4.1 Starting phase (I)**

Timeframe: M1-M9

Activities during the starting phase of Task 20 are limited to its official establishment within IEA Hydro and kick-off event with the experts group. It is planned to include the following activities:

- [I-A.1] Questionnaire
- [I-A.2] Administrative work
- [I-A.3] Kick-off meeting

The first activity (I-A.1) is a questionnaire listing all the potential interests and advantages in participating this task designed for IEA Hydro members around the world.

The second activity (I-A.2) is planned for any remaining administrative work and preparation of this Annex document to be presented to IEA Hydro and for approval by the Executive Committee.

The third activity (I-A.3) will be the kick-off meeting to Task 20. This event will be organized to invite participants from other IEA Hydro Tasks as well as other experts who hasn't been involved in IEA Hydro activities before but are interested in similar activities.

The event is planned as an online meeting. During the event the details to the five goals are planned to be finalized. The meeting outcomes will also serve as an input to the content presented on the IEA Hydro website. In addition to the scientific discussions around the objectives, another action point will be added to the Agenda of the Kick-off meeting. A Task-force is planned to form from the Task participants with the aim to monitor calls and other opportunities where international collaboration is possible among any of the task participants. This task-force is planned to remain in action with reporting duty at the expert's group meetings during the entire period of Task 20.

## **4.2 Operating phase (II)**

Timeframe: M10 – M40

Activities during the operating phase of Task 20 consists of several types of actions. The main phase is planned to last two years and a half with the following activities, presented not necessarily in chronological order:

- [II-A.1] Regular meetings with the experts group with reports from the Task-force
- [II-A.2] Task-force actions identifying relevant calls
- [II-A.3] Creation of five factsheets (following 5 major goals)
- [II-A.4] Organize a seminar and/or a special session at a selected international conference
- [II-A.5] Write a white paper in alignment with the five major goals

II-A.1 activity with Experts's meeting are planned frequently throughout the Task 20 period. All the Task meetings are planned to include an agenda point for the Task-force report.

In II-A.2 the Task-force shall communicate separately in between expert meetings (II-A.1) to summarize calls and other opportunities suitable for international collaboration between the task participants. Calls and opportunities are of an interest ranging from national projects with bilateral agreements for international partners to continental calls.

The aim with II-A.3 is to create five factsheets, which intend to provide an overview with the problems – solutions associated with the Task 20 objectives (five major goals).

With activity II-A.4 the plan is to propose and organize a seminar or special session during a selected conference (at a conference, summit or ExCo meeting).

Activities II-A.5 is coordinated work to write white papers following the five main objectives of Task 20. They shall include literature review, a general overview following the objectives and report best practices from different countries.

### **4.3 Closing phase (III)**

Timeframe: M41-M45

Activities during the following phase are planned as follows:

- [III-A.1] Creation of the Final report from Task 20
- [III-A.2] Workshop for Task participants and other IEA Hydro Task and country representatives

The first activity shall provide a handbook to address the four research topics of the five main objectives from Task 20. The document is based on the II-D.7 deliverables with an overall guideline to the reader on how to achieve best practices.

The second activity, III-A.2 will be organized as a workshop open for IEA Hydro participants. The aim of the event is to discuss the relevant topics for either Phase of Task 20 or to a new Task within IEA Hydro.

## **5 DELIVERABLE AND DISSEMINATION OBJECTIVES**

### **5.1 Dissemination during Starting phase (I)**

Dissemination during this phase is limited to one item only:

- [I-D.1] Questionnaire

We have conducted a questionnaire survey that lists all the potential interests and advantages in participating this task designed for IEA Hydro members.

### **5.2 Dissemination during Operating phase (II)**

Dissemination during the main phase of Task 20 reflects the activities from the same period:

- [II-D.1] Factsheet 1.
- [II-D.2] Factsheet 2.
- [II-D.3] Factsheet 3.
- [II-D.4] Factsheet 4.
- [II-D.5] Factsheet 5.
- [II-D.6] A seminar and/or a special session during a conference dedicated to Task 20
- [II-D.7] White papers for five major objectives

The target audience for the deliverables shall include the scientific community, industry and policy-makers. Direct products (deliverables) from the main phase (II-D.1-5 and II-D.7) shall be available on the IEA Hydro website or other social platforms for the scientific and industrial communities (e.g., LinkedIn, ResearchGate) and accessible to the target audience.

Live disseminations shall be co-organized together with the official coordinators of the selected international events (II-D.3) where such dissemination will take place. Potential international events for dissemination are: HYDRO conferences, IAHR World Congresses.

### **5.3 Dissemination during Closing phase (III)**

Dissemination during the closing phase is planned with the following item only:

[III-D.1] Final report from Task 20.

[III-D.2] Executive summary of the Final Report from Task 20.

Similar to other deliverables from the main phase, the Final Report together with its executive summary shall be available on the IEA Hydro website, with further dissemination at the social platforms for the scientific and industrial communities (e.g., LinkedIn and ResearchGate).

## **6 Addressing seven priority areas for IEA Hydro TCPs**

IEA Hydro along with the IEA headquarter has set seven priority areas to engage new research, collaboration and dissemination of sustainable hydropower. The Tasks are supported to address several of them during their period. The priority areas are the followings:

1. Move hydropower up the energy and climate policy agenda
2. Enforce robust sustainability standards for all hydropower development with streamlined rules and regulations
3. Recognise the critical role of hydropower for electricity security and reflect its value through remuneration mechanisms
4. Maximise the flexibility capabilities of existing hydropower plants through measures to incentivise their modernisation
5. Support the expansion of pumped storage hydropower
6. Mobilise affordable financing for sustainable hydropower development in developing economies
7. Take steps to ensure to price in the value of the multiple public benefits provided by hydropower plants

Task 20 will utilize digital twin technology to enhance hydropower flexibility by creating virtual models that optimize plant performance in real time. As power systems integrate increasing shares of variable renewable energy, existing hydropower plants must evolve from providing steady baseload output to delivering fast, flexible balancing services. Digital twin technology—a real-time virtual replica of a physical hydropower system—offers a transformative pathway to unlock these flexibility capabilities. By coupling real-time sensor data, physics-based simulations, and artificial intelligence, digital twins enable operators to predict and optimise plant behaviour under diverse hydraulic, mechanical, and electrical conditions. They allow engineers to test new operating modes virtually—

such as faster start-ups, higher ramping rates, or extended part-load ranges—without risking damage to actual equipment. This leads to smarter, safer, and more responsive operations.

Through predictive analytics, digital twins can anticipate stress, fatigue, and cavitation across turbines and penstocks, allowing maintenance and operation strategies to be dynamically adjusted. This ensures that increased cycling and frequent load variations do not reduce reliability or lifespan. Additionally, plant-level digital twins can be integrated into basin-scale or grid-level twins, enabling coordinated operation among cascaded reservoirs and stations to optimise water use, power output, and environmental flows in real time. In doing so, hydropower can act as a flexible, fast-response resource that stabilises renewable-heavy grids—essentially functioning as a digital-enabled “water battery.” By improving situational awareness, predictive control, and system coordination, digital twins transform conventional hydropower into intelligent assets capable of delivering advanced flexibility services for the evolving energy landscape.

To realise these benefits, policy incentives and modernization measures must encourage digital transformation across the hydropower fleet. Governments and regulators can introduce performance-based incentives that reward measurable flexibility services—such as rapid ramping or frequency regulation—verified through digital twin analytics. Public funding, grants, or tax credits can support digital retrofits, including sensor installation, control system upgrades, and data integration. At the market level, ancillary service and capacity mechanisms should monetise flexibility so operators can earn revenue from their digital-enhanced responsiveness. Regulatory frameworks should also recognise model-based validation from digital twins as acceptable proof of improved performance, reducing testing costs. By linking financial rewards with verified flexibility gains, these incentives create a positive feedback loop that accelerates digital modernization, extending asset life, boosting system efficiency, and ensuring hydropower remains a cornerstone of a reliable, low-carbon energy system.

**7 Summary of Milestones of Task 20**

All the deliverables and milestones from the different phases of Task 20 are summarised by the end of the application in separate tables. The following table provides an overview of the milestones with an estimated deadline (by project month) for each of them. .

Topic	Description of milestones	Deadline
Data Acquisition	Monitoring and perception of hydropower units	M24
	Data transmission and storage	M24
	Data preprocessing and integration	M27
Model Construction	3D geometric model of hydropower units	M30
	Physics & Behavior models of hydropower units	M33
	Rule model of hydropower units	M39
DT Deployment and Application	DT integration and deployment of existing infrastructures	M45
	Intelligent application development based on DT	M45
	Comprehensive evaluation of power plant status	M30

Retrofitting of Old Stations (Optional)	Research on practicality-oriented application scenarios	M36
	Other research subtopics (TBD)	

Phase	Description of milestones	Deadline
I	Questionnaire	/
	Kick-off meeting	M3
	Proposal Task Force establishment	M6
II	Organized seminar/special session at a selected international conference	M24
	Organized 1-day meeting (physical) with the expert group associated with an international conference	M33
	Organized 1-day workshop associated with an international conference	M42
III	Organized 1-day workshop to disseminate compiled knowledge of Task 20	M43

The final table of the document summarizes the deliverables from each phase of Task 20 with their proposed deadlines.

Phase	Description of deliverables	Deadline
I	Teaser of IEA Hydro Task 20	M15
II	Factsheet in alignment with the first objective of Task 20	M16
	Factsheet in alignment with the second objective of Task 20	M17
	Factsheet in alignment with the third objective of Task 20	M18
	Factsheet in alignment with the fourth objective of Task 20	M19
	Factsheet in alignment with the fifth objective of Task 20	M20
	White report on the Task 20 objectives (five major goals)	M39
III	Final report from Task 20	M43
	Executive summary of the final report from Task 20	M45

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