2 | 2023

#HydrolinkMagazine

hydrolink

IAHR AIRH
International Association for Hydro-Environment Engineering and Research
Hosted by Spain Water and IWHR, China
IAHR.org

EDITORIAL

Dr Angelos N. Findikakis
Hydrolink Editor

The fast growth of hydroelectric power in the last century continues today. Last year the total installed capacity of hydropower in the world was close to 3,400 GW and its total energy generation exceeded 4,300 TWh, being the largest renewable energy source.

This issue of Hydrolink includes six articles that describe recent innovations in different aspects of hydropower. Three of these articles describe collaborative efforts in Europe aimed at advancing the use of hydropower, the HYDROPOWER EUROPE Forum, and the projects ALPHEUS and XFLEX HYDRO, all supported by the European Union's Horizon 2020 program.

The HYDROPOWER EUROPE Forum is working to develop a Research and Innovation Agenda and a Strategic Industry Roadmap for the hydropower sector with the vision of hydropower serving as a catalyst for the successful energy transition in Europe. The European Technology and Innovation Platform was organized by the HYDROPOWER EUROPE Forum to identify the most important research and innovation hydropower projects, required strategic actions, ways to increase public awareness about the role of hydropower in the transition to clean energy, and how hydropower can work within the framework of the Water-Energy-Food Nexus and contribute to the achievement of the Sustainable Development Goals of the United Nations.

ALPHEUS, a collaborative effort of several research institutes, aims at improving the efficiency of low-head pumped storage. This project includes the development of higher efficiency reversible pump turbines; the development of a variable speed power takeoff and control system for pump-turbines to maximize opportunities for grid support; investigations into the electrical behavior of pumped storage in terms of a grid compliant and grid supportive manner; the assessment of sites along the periphery of the North Sea for potential low head pumped storage projects; and the construction of a complete 30 kW physical model to perform tests under realistic head conditions.

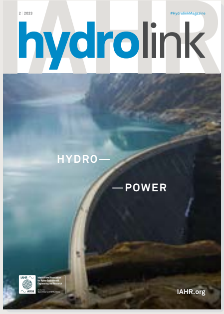
XFLEX HYDRO, a consortium of 19 partners from six countries, focuses on technological developments to enhance the flexibility of the electric power system by improving the efficiency, maximizing the performance and ensuring high availability of hydroelectric power plants. It is working at seven hydroelectric power plants in Portugal, Switzerland, and France to demonstrate new technologies. One of them is the operation of a pumped storage power station in hydraulic short circuit mode, during which the pump operates at fixed power set point, and a portion of the pump discharge is bypassed by the turbine to regulate the power drawn from the grid according to frequency control requests. This has been successfully demonstrated at the Grand Maison pumped storage plant in the French Alps.

Another article discusses a program that demonstrated that it is possible to enable low-head hydro power plants using Francis turbines to generate power over a wider operating range. This was accomplished by replacing the runner with one that includes an inter-blade hydrofoil that introduces air to achieve optimal dissolved oxygen levels for downstream aquatic ecosystems. Based on specially collected data and model simulations it was possible to double the operation range of the turbines. In addition, the results of the simulations showed that the increased flexibility of the low-head Francis turbines contributes to grid system resilience and reliability.

The development of a software tool for integrating detailed hydropower plant characteristics with water availability is described in another article. This development is carried by the Electric Power Research Institute sponsored by the United States Department of Energy. The new tool analyzes and evaluates energy and flexibility services and uses a cloud-based calculation engine that co-optimizes unit-level dispatch for energy generation, regulation, and spinning reserve, subject to water availability. Among other applications, this tool can be used to improve the dispatch process, calculate the impact of water passage requirements, evaluate the impact of future hydrologic conditions, assess the flexibility potential for non-powered dams and greenfield development, and predict the flexibility benefits from efficiency improvements.

Finally, an article by the Three Gorges Corporation describes the recently completed Baihetan station in China, the world's second largest hydropower project, with its million-kilowatt capacity units being the largest in the world. A significant innovation in the construction of its massive concrete dam was the use of a new low-heat silicate cement, which made it possible to effectively control the maximum temperature of concrete after pouring.

As it continues to evolve and improve its performance through innovation, hydropower has a significant role to play in the global effort to reach Net Zero by 2050, both by continuing to produce clean energy and by contributing to grid flexibility through pumped storage projects supporting non-dispatchable energy sources such as wind and solar.



IAHR
International Association for Hydro-Environment Engineering and Research

IAHR Global Secretariat
Madrid Office
Paseo Bajo Virgen del Puerto, 3
28005 Madrid, SPAIN
T +34 91 335 7908 | F +34 91 335 7935

Beijing Office
A-1 Fuxing Road, Haidian District
100038 Beijing, CHINA
T +86 10 6878 1128 | F +86 10 6878 1890

iahr@iahr.org
www.iahr.org

Cover picture: Moosersperre Dam, part of the Kaprun pumped-storage scheme, Austria
ISTOCK BY GETTY IMAGES
DESIGN BY TRES ESTUDIO CREATIVO

ISSN: 1388-3445

IAHR HYDROLINK
2 | 2023

GUEST EDITOR

Erfaneh Sharifi

Dr Erfaneh Sharifi is a Senior Water Resources Engineer supporting the Water Innovation for a Resilient Electricity System Initiative within the US DOE Waterpower Technologies Office.

She has worked on different projects in collaboration with scientists and engineers internationally in academia, government, industry, and nonprofit agencies.

The energy crisis in Europa reveals the importance of reliable hydropower as a catalyst and enabler for the clean and safe energy transition

By Anton J. Schleiss, Jean-Jacques Fry and Mark Morris

Situation of hydropower in Europe

Hydropower has a long tradition in Europe, contributing significantly during the first half of the last century to the welfare and industrial development of most countries across the continent. Today, reaching nearly 650 TWh of annual generation in an average hydrological year, the economically feasible hydropower potential within Europe (including Turkey) is approximately 65% utilized thus far (**Figure 1**). The installed capacity in Europe including Turkey reaches almost 230 GW today. Since 2013 annual hydropower and the total installed capacity has stagnated close to today's values. It should be noted that in principle the yearly hydropower production is influenced by the hydrological situation each year.

Figure 2 illustrates a snapshot of the current situation for hydropower usage and untapped potential in countries within the European region. It can be noted that many countries still have considerable potential for development. The countries highlighted with a "sun star" in **Figure 2** have developed less than 50% of the economically feasible potential, should the market conditions demand for it. For 14 countries the share of hydro in the overall electricity generation is between 25% and 50%, for three countries between 50% and 90% and for another two counties higher than 90%. This demonstrates that in more than half of the countries in Europe, hydropower represents a significant share of electricity generation, which is important for the success of a safe energy transition to renewable sources.

Nevertheless, relatively little investment has been undertaken over the last 15 years, as can be seen in **Figure 3** which shows the installed capacity under construction. After 2011, a quite significant increase in the construction of new power plants reaching almost 10,000 MW can be seen. This may be attributed to the Fukushima catastrophe of 2011, leading many countries to redefine their energy strategy towards renewable sources, such as hydropower, alongside the planned phasing out of nuclear energy. Since 2015, however, construction activity has decreased to some 3000 MW in 2021.

The low investment level can be attributed to low electricity prices on the European spot market, due to the following reasons:

- Production capacity in Europe was too high
- Cost of CO_2 certificates were very low, doing little to dissuade conventional thermal methods
- Market distortion (change of merit order for hydropower) due to the high subsidies provided for other renewable energy sources such as solar and wind.

Thus, under such market conditions hydropower generation was strongly penalized, until the start of the energy crisis in 2022 triggered by the war in Ukraine. However, the energy crisis reveals the vital role of reliable hydropower to help ensure a safe supply of electricity in the coming winters across Europe. Storage and pumped-storage hydropower will be the most vital source of electricity supply to avoid blackouts under critical situations.

Due to the energy crisis, the attractiveness of the extension and upgrading of existing hydropower plants, with the purpose of making them more flexible through the refurbishment of equipment and increasing storage where possible, together with the construction of new pumped-storage power plants has increased again strongly in countries with high storage potential. Furthermore, in many countries a significant amount of untapped hydropower potential still exists. However, in view of environmental and socio-economical constraints, the partial use of this remaining potential is extremely challenging and can be reached only through innovative and sustainable solutions for new hydropower plants.

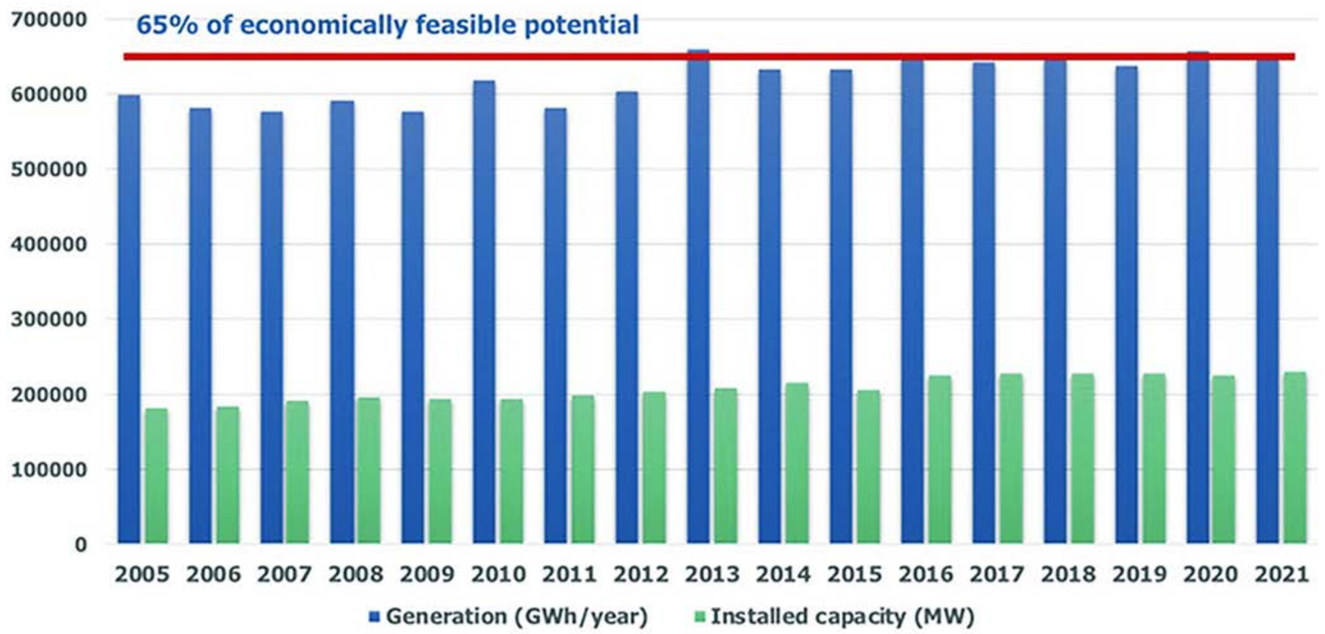


Figure 1 | Evolution of yearly production and installed capacity of hydropower in Europe including Turkey since 2005 (according to Hydropower & Dams World Atlas 2022).

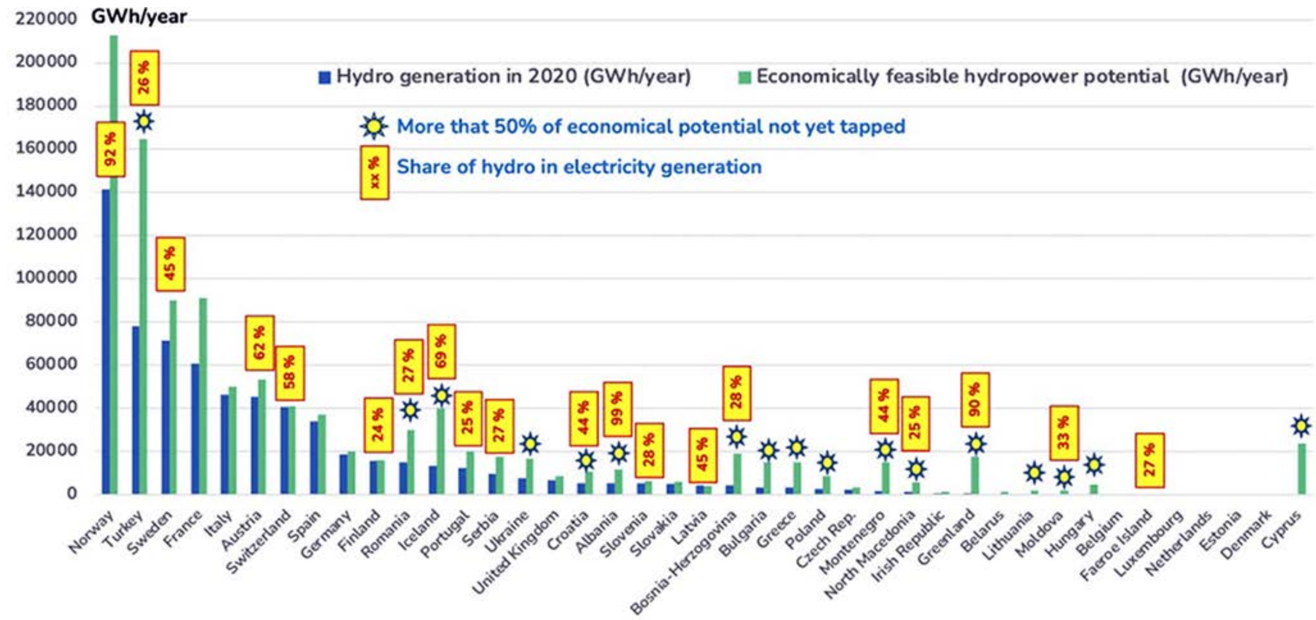


Figure 2 | Generation and extension potential of hydropower in countries in the European region (according to Hydropower & Dams World Atlas 2021). The countries having developed less than 50% of their economical feasible potential (assuming market conditions have demand for it) are highlighted with a "sun star". The share of hydro in the electricity generation is indicated for the countries with a share of more than 25%.

Advantages of hydropower

Hydropower in Europe and worldwide has many advantages including:

- Renewable energy without direct emission of CO_2
- Unbeatable energy gain or pay-back during a long project life
- Excellent efficiency, with reliable production easily adapted to the demand (very flexible and timely peak energy)
- In-country, independent energy-sector, job creation and financial resources in remote areas (taxes and concession fees)
- Improvement of infrastructure and attractiveness for tourism
- Contribution to flood and drought protection (drinking water, irrigation, flood routing), as many hydropower dams are multi-purpose
- Facilitation of navigation for the large rivers in Europe

Looking in more detail at the life cycle analysis, hydropower is by far the best option in view of sustainability. Regarding the so-called recovery factor or energy pay back ratio of primary energy, which is obtained by the total expense of non-renewable energy (direct and indirect) during a lifetime to operate an installation, hydropower is unbeatable[1]. For hydropower plants with reservoirs created by dams the energy pay back ratio is between 205 and 280, and for run-of-river power plants between 170 and 270 considering a technical life of 80 years. In fact, these numbers exceed very clearly those attained by other renewable energies such as, for example, solar photovoltaic (3 to 6) and wind (18 to 34), whose technical life may be expected so far to be only 20 years. Their recovery or gain factors are rather small today, but important technical progress can be expected in the future. On the other hand, thermal power plants producing electricity with non-renewable fuels have, as expected, a much lower energy pay back ratio which is close to 1 or even below (for example a coal fired closed cycle powerplant is 0.97).

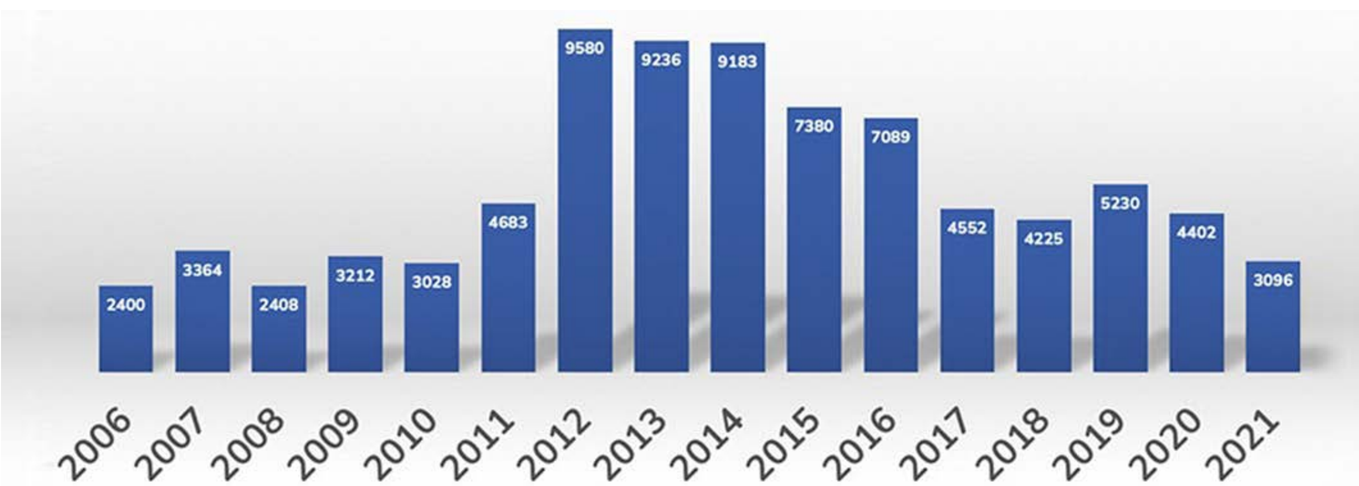


Figure 3 | Hydropower capacity (MW) in Europe under construction since 2006 (according to Hydropower & Dams World Atlas 2022 without Turkey).

Furthermore, recent life-cycle analysis also confirms that hydropower can reduce greenhouse gas emissions (GHG) significantly, even by developing only a part of the remaining economically feasible hydro potential.

A study in Switzerland revealed that, for hydropower, the equivalent CO_2 emissions of greenhouse gases is very small compared to other energy generation types and is caused mainly by the acquisition of materials required for construction and maintenance[2, 3]. Run-of-river power plants produce 3.8 g CO_2 - equivalent/kWh and storage power plants 5.5 to 8.3 g/kWh. For nuclear energy, these emissions are between 14.2 and 15.9 g/kWh depending on the type of reactors. For the new renewable energy sources like wind and solar (photovoltaic) the values of emissions are 17.3 g/kWh and 41.7 g/kWh respectively. Biogas power plants with thermal-power coupling produce 77 g/kWh. These values are still relatively small compared to the emissions of gas power plants (613.7 g/kWh) and coal power plants (1108 to 1221 g/kWh).

Challenges for future development of hydropower and dams in Europe

The future development of hydropower and dams in Europe must overcome the following challenges[4]:

- The change of production potential due to the effects of future climate forcing, which are expected to impact water availability (glacier retreat, snow accumulation and melt, stream-flow regimes, and sediment production and transport) as well as the operational safety of structures in view of new natural hazards (floods, slope instabilities, etc.);
- The efficiency improvement of existing hydropower plants (HPPs) and reservoirs, which can be achieved by their expansion to allow more flexible operation to accommodate new and highly fluctuating demands;
- The contribution of new technological solutions to adapt existing infrastructure in view of increasing their efficiency of production and achieving higher operation flexibility during seasonal and daily peak demands, whilst maintaining the same level of (infra)structural safety and supply security;
- The assessment of the effects of HPPs new and harsher operation regimes and increased numbers of small hydropower plants on aquatic ecosystems and the development of strategies to reduce these impacts (e.g. by developing innovative strategies of environmental flow releases).

Hydropower and dam projects often provoke controversial discussions. To gain wide acceptance and to obtain a win-win situation between all stakeholders such large water infrastructure projects have to be designed as multi-purpose projects by multidisciplinary teams with a complex system approach. This requires excellence in engineering sciences and management and innovative planning approaches.

Hydropower Europe Forum: The vision for hydropower development in Europe

The ambitious plan for European energy transition towards becoming carbon-neutral by 2050 is one of the greatest endeavours of our generation. The uptake of renewable energy sources (RES), mainly solar and wind, is consistently growing in many European countries, proliferated by the mandatory phase-out of fossil fuels. This uptake of RES also creates obstacles, such as difficulty in aligning electricity generation with demand. Hydropower, as a reliable renewable, already supports integration of wind and solar energy into the supply grid through flexibility in generation as well as its potential for storage capacity. These services are and will be indispensable on the path to achieve the desired energy transition in Europe, and worldwide. Hydropower has all the characteristics to serve as an excellent enabler and catalyst for a successful energy transition.

There is still untapped potential in hydropower, which allows hydropower to perform this role even more strongly. However, this will require a more flexible, efficient, environmentally and socially acceptable approach to increasing hydropower production to complement other renewable energy production.

The Hydropower Europe Forum[5], supported by the EC under the Horizon 2020 programme LC-SC3-CC-4-2018, was started in 2019 with the ambition to develop a Research and Innovation Agenda (RIA) and a Strategic Industry Roadmap (SIR) for the hydropower sector, based upon the synthesis of technical fora and transparent public debates through a forum that gathers all relevant stakeholders of the hydropower sector. Through an extensive program of review and consultation addressing the entire hydropower sector and stakeholders (including construction, production, environmental and social issues), the Hydropower Forum provides a focal point for reviewing and developing hydropower in Europe, and subsequently European hydropower in the wider world. Building from this extensive programme of consultation, the Hydropower Europe Forum has developed a strategic RIA and a SIR, towards implementation of the vision "Hydropower as a catalyst for the successful energy transition in Europe"[6]. In more detail, the vision for hydropower development in Europe as defined by the Hydropower Europe Forum comprises the elements shown in **Figure 4**.

Increasing hydropower production through the implementation of new environmental friendly, multipurpose hydropower schemes and by using hidden potential in existing infrastructures.

Increasing the flexibility of generation from existing hydropower plants by adaptation and optimization of infrastructure and equipment combined with innovative solutions for the mitigation of environmental impacts.

Increasing storage by the heightening of existing dams and the construction of new reservoirs, which have to ensure not only flexible energy supply, but which also support food and water supply and thus contribute to the WEF NEXUS and achievement of the SDGs of the United Nations.

Strengthening the contribution of flexibility from pumped-storage power plants by developing and building innovative arrangements in combination with existing water infrastructure.

Figure 4 | Vision for the development of hydropower in Europe.

Research and innovation needs and strategic actions required for further develping hydropower in Europe

The Research and Innovation Agenda developed by the Hydropower Europe Forum provides recommendations on Research & Innovation (R&I) priorities for hydropower to the EU institutions and national authorities to contribute towards shaping public spending for R&I. Through wide consultation involving all relevant hydropower stakeholders, the priority R&I themes and topics, the rationale behind them and their expected outcomes were collected. These themes and topics covering the entire hydropower value chain and were clustered into the following seven thematic groups addressing the challenges which the European hydropower sector must address, namely:

- Increasing flexibility
- Optimisation of operations and maintenance
- Resilience of electromechanical equipment
- Resilience of infrastructures and operations
- Developing new emerging concepts
- Environmental-compatible solutions
- Mitigation of the impact of global warming

In total, 18 research themes including 80 detailed research topics spread across have been formulated, building from the wide consultation feedback. After several workshops with the Consultation Expert Panel the priorities, the suggested time horizon for when the call should be initiated, as well as the recommended funding scheme for all research themes were defined[7]. In **Figure 5** the research themes with high to very high priorities are illustrated and grouped according to the above-mentioned challenges.

The Strategic Industry Roadmap, also developed through a substantial programme of consultation, comprises in total 11 strategic directions including some 40 detailed actions (ranging from regulation framework to social acceptance and innovative environmental strategies)[8]. The most important three key strategic directions with actions needed to support the role and development of hydropower are summarized in **Figure 6**.

The full RIA and SIR reports and the corresponding extended executive summary brochures as well as a YouTube presentation on the main outcomes of the Hydropower Europe Forum can be found under https://hydropower-europe.eu.

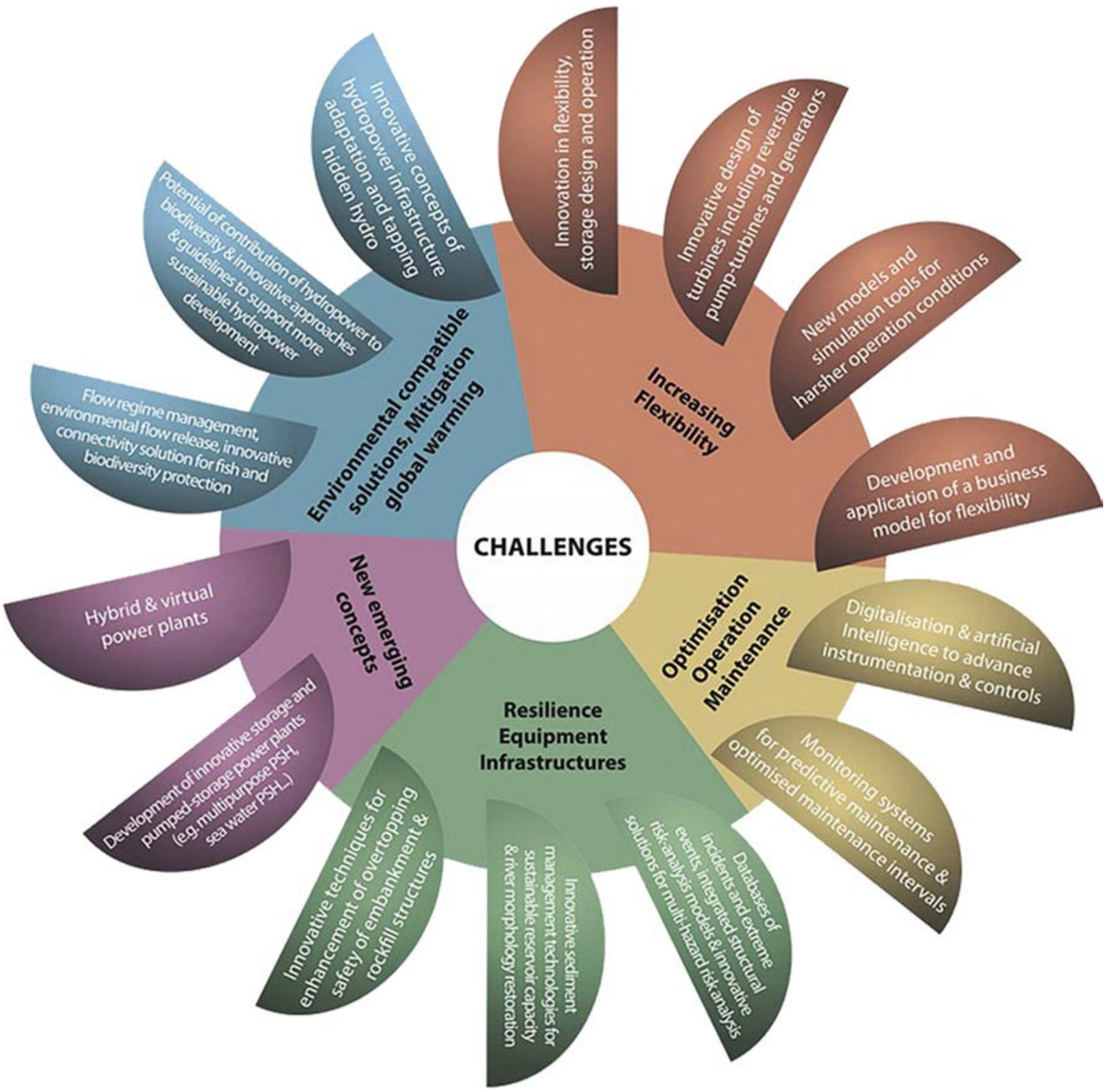


Figure 5 | Suggested research themes by Hydropower Europe with high to very high priority grouped according to the challenges which hydropower must address.

Providing economic and legal support for flexibility and storage	Preserving biodiversity and improving river ecosystems	Raising public awareness, increasing societal resilience and local employment
1 | Improvement of flexibility markets.	1 | Collect best practice for sustainability and biodiversity protection.	1 | Increase public awareness with communication and dissemination.
2 | Best practice for investing under uncertainties.	2 | Increase the knowledge on environmental impacts.	2 | Develop best practices for sustainability for successfull projects and win-win situations.
3 | Development of a more pertinent regulation framework.	3 | Develop innovative compensation measures for the protection of biodiversity.	3 | Increase security, decentralization and independence of the European energy system with PSH.
	4 | Develop comprehensive approaches allowing compromises.	4 | Give a collaborative platform to the hydro sector.

Figure 6 | Key strategic directions with actions needed to support the role and development of hydropower in Europe.

ETIP HYDROPOWER

Unifying the voices of hydropower in Europe

The European Technology and Innovation Platform (ETIP) is a community whose primary purpose is to define R&I priorities for its sector. Its secondary purpose is to overcome barriers to the deployment of R&I outcomes, e.g., industrial strategy, market opportunities, exploitation of research results, international cooperation, education, environmental and social impacts. There is a need for a unified hydropower industry to be represented and recognized at a European level. The Hydropower Europe Forum provided a first opportunity to gather some 650 stakeholders representing all the sectors of the value chain. Under the ETIP HYDROPOWER project (https://etip-hydropower.eu) started in September 2022, the hydropower forum will continue to grow and offers an ideal opportunity to help unify the voices of hydropower in Europe[9].

The ETIP HYDROPOWER aims to be a recognised interlocutor for the European Commission, Member States and Associated Countries about the hydropower sector specific R&I needs. ETIP HYDROPOWER foresees working relationships with the relevant national/regional/EU-level platforms to ensure synergies between EU, national and regional activities. In more detail, ETIP HYDROPOWER will answer the following questions:

- Which research and innovation projects are the most important such that hydropower can fulfil the role of an enabler and catalyst in the energy transition?
- Which strategic actions have to be taken when, such that hydropower can fulfil the role of an enabler and catalyst in the energy transition?
- How can public awareness be increased for hydropower in the transition to a clean energy system focusing towards a zero-emissions target?
- How can hydropower projects be carried out to create win-win situations with other renewables and other services contributing to the Water-Energy-Food Nexus and the achievement of the SDGs of the United Nations?
- What form of sustainable associate organisation representing the hydropower sector is required to ensure the vital role of hydropower in the energy transition?

ETIP HYDROPOWER will address these questions and challenges with working groups identified and launched based on consultation with the hydropower sector willing to participate with the sustainable associate organization beyond the ETIP lifetime. Potential working groups cover a wide range of topics: economy, environment, equipment, structures, pumped storage hydropower, small hydro, digitalization, communication, market rules, legal frameworks etc. depending upon the specific need of the sector. Working groups will also include Civil Society Organisations for the identification of potential social impacts of hydropower.

Conclusions

Built from the Hydropower Europe Forum, ETIP HYDROPOWER will help to ensure that hydropower can play the vital role of a catalyst and enabler in the transition to a clean and safe energy system in Europe. Hydropower has proven to be a reliable supplier in the energy crisis. Is important contribution to secure storage with the lowest indirect CO_2 emissions amongst all forms of renewable energy will become even more important in the energy transition towards the achievement of climate neutrality by mid-century. ETIP HYDROPOWER will help to unify the voices of hydropower in Europe and worldwide, to increase public awareness on its catalyst and enabler abilities, as well as motivate innovative collaborative research towards environmentally compatible solutions. Besides electricity supply, hydropower projects can offer other services which are important to help mitigate climate change effects, like water supply, contribution to flood and drought protection with potential for recreational and tourism activities and facilitating navigation on large rivers.

Acknowledgement

ETIP HYDROPOWER has received funding from the European Union's Horizon Europe research and innovation programme under grant no 101075620. Project partners are: International Commission on Large Dams (ICOLD), European Association for Storage of Energy (EASE), European Renewable Energies Federation (EREF), Association of Europe and Renewable Energy Research Centres (EUREC), International Hydropower Association (IHA), Samui France SARL (SAMUI), VGBE energy (vgbe) and ZABALA Brussels SPRL (ZABALA).

References

1 | Schleiss, A. J. (2000). The importance of hydraulic schemes for sustainable development in the 21st century. Hydropower & Dams (2000), 7(1): 19-24.

2 | Frischknecht, R.; Itten, R.; Flury, K. (2012). Treibhausgas-Emissionen der Schweizer Strommixe. Studie im Auftrag des Bundesamtes für Umwelt (BAFU). ESU-services Ltd. Kanzleistrasse 4, 8610 Uster.

3 | Krebs, L.; Frischknecht, R. (2021). Umweltbilanz Strommixe Schweiz 2018. treeze Ltd., fair life cycle thinking, Kanzleistr. 4, CH-8610 Uster, www.treeze.ch

4 | Schleiss, A.J. (2019). The importance of hydropower development for the energy transition in Europe. Proceedings of the 11th ICOLD European Club Symposium, Chania, Crete, October 2 to 4, 2019 (online).

5 | Fry, J.-J.; Schleiss, A.J; Morris, M. (2018). The Hydropower-Europe forum and the technology roadmap. Hydropower & Dams, 25 (5): 53-56.

6 | Fry, J.-J.; Misech, A.; Morris, M; Schleiss, A.J. (2022). Research themes and strategic actions to promote hydropower as a catalyst for the energy transition in Europe. Hydropower & Dams. 29(3): 37-47.

7 | HPE Hydropower Europe Forum (2021). Research and Innovation Agenda (RIA). Report WP4-DIRp-53. (https://hydropower-europe.eu).

8 | HPE Hydropower Europe Forum (2021). Strategic Industry Roadmap (SIR). HPE report no. WP4-DlRp-54. (https://hydropower-europe.eu).

9 | Fry, J.-J.; Garcia, J.; Morris, M.; Schleiss, A.J. 2023. The need for a unified European hydropower voice. Energetyka Wodna, 45(1):14. ISSN 2299-0674.

Anton J. Schleiss

Dr Anton J. Schleiss obtained a Doctorate of Technical Sciences on the topic of pressure tunnel design in 1986 at ETH Zurich. He worked for 11 years for Electrowatt Engineering Ltd (now Pöyry-AFRY). In 1997, he was nominated full professor and became Director of the Laboratory of Hydraulic Constructions (LCH) of the Ecole Polytechnique fédérale de Lausanne (EPFL). He supervised more than 50 PhD and Postdoc research projects. Since 2018 he is professor emeritus at EPFL. He is the honorary President of the International Commission on Large Dams (ICOLD) and has received IAHR Honorary Membership in 2022. With more than 40 years of experience he is regularly involved as a consultant and expert in large water infrastructures projects including hydropower and dams all over the world. He was the coordinator of Hydropower Europe and is part of the management team of ETIP HYDROPOWER project.

Jean-Jacques Fry

Dr Jean-Jacques Fry), graduated in 1974 in Hydraulics from Ecole Nationale Supérieure d'Hydraulique de Grenoble, France, obtained a PhD on Soil Mechanics at Ecole Centrale de Paris (1977). Since 2019, he is currently independent consultant. He was the chairman of the European Club of ICOLD from 2017 to 2022. He built in the managing team of the "Hydropower Europe" forum, a CSA project of EU H2020 and is part of the management team of ETIP HYDROPOWER. He is currently the expert who supervised the constructions of the upper and lower reservoirs of Abdelmoumen Hydropower Pumped Storage Scheme in Morocco (2020-2024).

Mark Morris

Dr Mark Morris is an Engineer working at the interface between research and practice, focussed on environmental hydraulics, hydropower and flood risk analysis / management. Mark works on a mixture of both research and specialist consultancy studies, in particular focussing on European and wider International research collaboration. Recent and ongoing activities include supporting and coordinating European research projects – such as the Hydropower Europe, ETIP HYDROPOWER and EcoAdvance projects, strategic planning for UK reservoir safety research and industry driven research into dam and levee surface erosion processes.

Towards enhanced power system flexible services, XFLEX HYDRO paves the way

Focus on hydraulic short circuit technologies for pumped storage power plants

By Jean-Louis Drommi and François Avellan

Aiming for a greener future, the European grid's need for increased flexibility has led the EU commission to call for innovation actions to further enhance flexible services from Hydro assets. XFLEX HYDRO is responding to this call by demonstrating that updated digitalization, hybridization, hydraulic short circuit and variable speed technologies can unlock a multitude of novel and expanded services for the long-standing hydro industry, thus paving the way towards a more sustainable future for the grid. Focusing on pumped storage hydro power plants, this article details how implementation of digitalization and hydraulic short circuit operation may improve frequency control of the grid.

XFLEX HYDRO Project

The EU Horizon 2020, now Horizon Europe, program aims to facilitate the extensive decarbonization of the energy sector across the European Union. One of the key strategies pursued paths followed by the EU is to seek solutions to build a low carbon and climate resilient future for the energy system mix. This is particularly crucial due to the increasing reliance on non-dis-patchable renewable sources, such as solar and wind power, which are subject to weather conditions, as well as market-induced imbalances. To address these challenges and enable the development of renewable sources, particularly in terms of frequency control, XFLEX HYDRO has explored flexibility enhancement opportunities through digitalization, battery hybridization, hydraulic short circuit operation and variable speed technologies. The goal of XFLEX HYDRO is to demonstrate, at an industrial scale (TRL7), how hydroelectric technologies can be leveraged to provide flexibility to the Electric Power System (EPS) while improving overall efficiency, ensuring high availability of Hydroelectric Power Plants (HPP), and maximizing their performance.

Through the demonstration of the system integration of hydroelectric flexible technology solutions such as fixed and variable speed electrical machines, pump power regulation, battery hybridization, advanced monitoring and digitalization, XFLEX HYDRO aims to establish a roadmap for the integration and utilization of these flexible technology solutions in various European hydroelectric power plants, i.e., run-of-river, storage and pumped storage of all sizes; being existing, uprated or new.

The objectives of the XFLEX HYDRO project are being addressed by a consortium of 19 partners from 6 countries. Coordinated by EPFL, Switzerland, the Consortium includes academic and research institutes, 3 consulting engineering companies, 3 major European electrical utilities, and 3 major European hydroelectric equipment manufacturers. The Consor-tium has been working on this 4-year project, representing more than 250000 working hours and an overall budget of EUR 18 million.

The seven HPPs for the demonstration of hydro flexible technology are scheduled by the partner utilities (ALPIQ, EDF, EDP) to implement specific features in each HPP, covering the full range of flexibility technologies to be demonstrated. It is worth mentioning that all demonstrators are among the most significant HPPs in operation in their respective countries, which demonstrates the confidence, involvement, and expectations that utility management places on the flexibility services provided by their hydro assets.

In Portugal, EDP operated demonstrators are the pumped storage power plant PSP Alqueva, the storage hydro power plants SHP Alto Lindoso and SHP Caniçada, and the variable speed pumped storage power plant PSP Frades II. In Switzerland, ALPIQ operates the pumped storage power plant PSP Z'Mutt, which is a part of the Grande Dixence hydroelectric scheme, specifically the Z'MUTT variable speed pump turbine unit 5. In France, EDF operated demonstrators are the run-of-river power plant ROR Vogelgrün on the Rhine River and the pumped storage power plant PSP Grand Maison in the Alps.

Flexibility

The "Flexibility" property considered for the electric power system, and specifically for generating assets, refers to the ability to adjust the operating set point in a controllable manner. This flexibility feature covers various time horizons, from milliseconds for electrical short circuit response, to several seconds for frequency support, and up to hours or even years for long-term energy storage. The XFLEX HYDRO consortium has surveyed the time horizons of the European Electric Power System (EPS) to establish a comprehensive framework for flexibility and the EPS support services that the HPPs can offer.

The technical requirements associated with different services are investigated, along with the placement of these services within current and emerging market mechanisms. The identified ancillary services that HPP can provide are the following:

- Synchronous inertia.
- Synthetic inertia.
- Fast Frequency Response (FFR).
- Frequency Containment Reserve (FCR).
- Automatic Frequency Restoration Reserve (aFRR).
- Manual Frequency Restoration Reserve (mFRR).
- Replacement Reserve (RR).
- Voltage/Reactive power.
- Black Start.

To complete the investigations, a comprehensive sorting matrix has been developed to compare HYDRO technologies with flexibility services within current and emerging market mechanisms. This matrix has been published as a public XFLEX HYDRO deliverable[1], and further refined in a subsequent stage[2].

PSPs: Pumped Storage Power Plants

The present article focuses on pumped storage power plants (PSPs) that have the capability to transfer significant amounts of energy from the grid to an upper storage reservoir and dispatch the energy on demand, with a pumping to generating energy cycle efficiency as high as 80%. PSPs support Transmission System Operators (TSOs) by balancing the power grid. They were installed at large scale, alongside large capacity nuclear and fossil fuel thermal power plants[3]. In 2021, the 62 GW PSP capacity installed in the Europe region represented 4.7% of the 1'322 GW total power generation capacity and only 0.3% of the total power generation of 3'672 TWh. Traditionally, the typical PSP operation schedule was a pumping mode at night and a generating mode during the morning and evening peaks, causing two daily mode changes. However, with the increasing integration of non-dispatchable renewable energy sources (RES) and the decommissioning of the conventional units that emit greenhouse gases, the power balancing requirements have drastically changed the operation schedule. First, the midday generation peak has disappeared, and secondly, the daily profile of power generation has been influenced by the "duck curve" shape with intraday multiple mode changes typically influenced by the massive wind and solar deployments. To support the evolving EPS flexibility needs in terms of control capability, fast frequency control, fast start/stop, fast generating to pumping modes transition, high ramping rate, inertia emulation, etc., the PSP hydroelectric unit technology benefits from three main breakthroughs: digitalization, variable speed electrical machines, and hydraulic short circuit operation. These breakthroughs enable advanced unit control and maintenance, enhanced range of head values, and an extended power regulation range from full pumping to full generating.

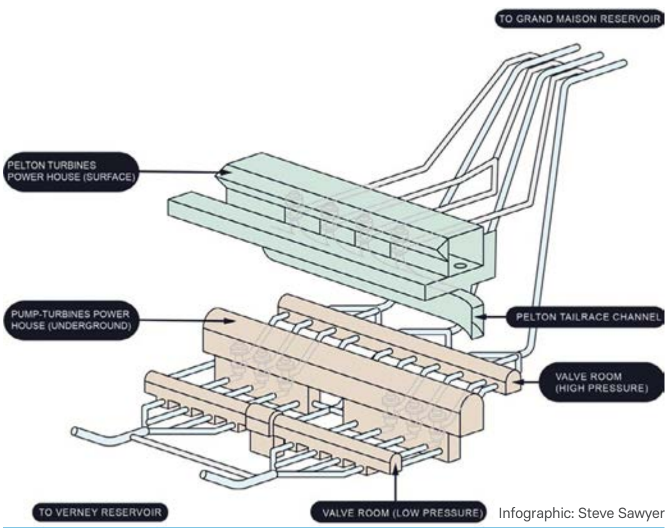
PSP and Hydraulic Short Circuit Operation

The PSPs may feature the following general arrangements of their hydroelectric units:

- Independent pump and turbine units.
- Ternary units featuring the pump and turbine hydraulic machines mechanically coupled with the motor-generator electrical machine on the same shaft.
- Independent reversible pump-turbine units.

Depending on these arrangements, specific pumping mode start-up must be addressed at the design stage of the PSP. In the case of ternary unit arrangements, the pump mode start up is achieved by the shaft coupled turbine driving all the rotating train. Therefore, the waterways must allow the pump and the turbine hydraulic machine to operate concurrently. This arrangement enables concurrent operation within the ranges of rated discharge values for both hydraulic machines, allowing the regulation of the power in pumping mode even if the pump cannot be regulated. This operation mode is known as Hydraulic Short Circuit (HSC). For instance, the 540 MW Kopswerk 2 in Austria and the 240 MW Veytaux II, installed in 2009 and 2017, are two PSPs featuring ternary units originally designed to operate in HSC mode to provide EPS support services. In HSC mode, the pump operates at fixed power set point, and a portion of the pump discharge is bypassed by the turbine to regulate the power drawn from the grid according to frequency control requests.

In the two cases of independent units' arrangements, the driving power at start-up may be provided by the next turbine unit. This can be achieved through electric coupling, either by back-to-back power coupling between the turbine generator and the pump drive or by power electronics of which rated power may require to reduce the pump start-up power value by dewatering and watering procedures at the pumping mode start. In these cases, depending on the PSP waterways, the extension to the HSC operating mode is still possible but may result in high hydraulic energy losses or undesired hydrodynamic phenomena such as flow instability, structure vibrations, or cavitation erosion. Therefore, thorough investigations must be



Infographic: Steve Sawyer

Figure 1 | View of the Grand Maison PSP including waterways, and powerhouse arrangement featuring 4 Pelton turbine and 8 pump turbine units.

Figure 2 | Aerial photography of Grand Maison PSD switch yard and top of the powerhouse. Photo by: Matthias Magg.

undertaken to implement the HSC mode of operation. This is exactly the case at the Grand Maison PSP.

Grand Maison and Hydraulic Short Circuit Operation

The Grand Maison PSP, part of the EDF Hydro asset, features a 1800 MW capacity, making it the largest capacity PSP in Europe and one of the ten largest PSPs in the world. The Grand Maison PSP was designed and built in the early 1980s as a complementary power source to the French nuclear power generation program. It uses excess energy during low demand periods, typically at night and over the weekends, and releases it during peak demand periods. This PSP includes both an under-ground and a surface powerhouses. The underground power-house consists of eight independent high-head 156 MW four stage reversible pump-turbine units operating at fixed speed and without any regulating ability, see Figure 1. The surface powerhouse (Figure 2) features four indepen-dent five jets Pelton turbine units with an uprated capacity of 170 MW each, which are fully adjustable and capable of provi-ding EPS support services.

Prior to the XFLEX HYDRO project, the PSP was operated with two basic modes: dispatchable power generating mode and pumping mode at fixed set points to transfer energy in-excess as potential energy to the 140 x 10^6 m^3 upper reservoir of Grand Maison by pumping from the Verney lower reservoir (see Fig. 3). Additionally, in PSP generating mode, the four Pelton turbines were able to provide both FCR and a FRR ser-vices to the EPS.

Grand Maison HSC Mode Roll-Out

In the framework of the XFLEX HYDRO project, the objective to enhance EPS Support Service provision even in pumping mode was achieved by extending the operation of the Grand Maison PSP to HSC operating mode. The Grand Maison waterways architecture allows two feasible options for HSC operation, as shown in Figure 4:

- Option 1, "Short Loop": HSC is established between one or more pump-turbines (in pumping mode) and the Pelton turbine located on the same penstock. The orange arrows in Figure 4 indicate the "Short Loop" between pump-turbine unit G3 and Pelton turbine unit G9, with flow diversion occurring at the marked bifurcation.
- Option 2, "Long Loop": HSC takes place between one or more pump-turbines (in pumping mode) and the Pelton turbine located on one of the two next penstocks. The green-blue arrows in Fig. 4 indicate the "Long Loop" between pump-turbine unit G6 and Pelton turbine unit G10, with flow diversion occurring at the tri-furcation. It should be noted that long and short loops may occur simultaneously.

Thorough numerical flow simulations[4] and field testing have been performed to assess the impact of the possible HSC mode operations on both the hydraulic structures and the hydroelectric units. Paying special attention to safety, systematic SIMSEN transient simulations have been performed to investigate the interaction between the pump and the turbine, the flow in bifurcations or the risks of cavitation. The most critical point, corresponding to a minimum of both the level in the surge tank and the pressure in the headrace tunnel, requires limiting HSC operation when the upper reservoir level reaches its minimum elevation value.

HYDRO-CLONE®, the SIMSEN based solution for real time Water Hammer/Surge Tank/Unit Transient Monitoring, was installed and calibrated to monitor the flow transients at any location of the waterways. The time history of the monitored surge shaft level elevation and the output of the Grand Maison PSP HYRO-CLONE® is plotted in Figure 5 during the transient generated by a pump start-up.

18 Months of HSC Mode Operation

Once all numerical simulations and monitoring studies had proven that the PSP could operate safely in HSC mode, the demonstrator was admitted on board the EDF generating fleet. This "industrial scale" trial aimed at producing a statistical database on the use of dispatchable pumping mode: whether it is used, when, and for how long. To understand the logic behind the "industrial scale" trial, it is worth noting that EDF's utility generating program is designed with a very simple objective: dispatchers

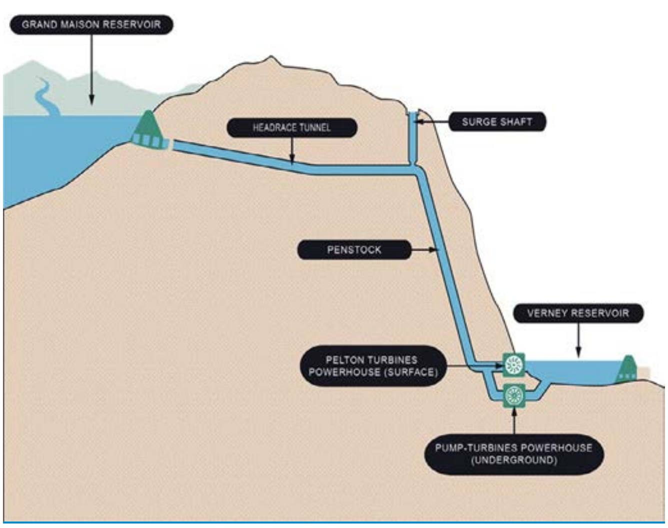


Figure 3 | Cut View of the Grand Maison PSP Waterways. Infographic: Steve Sawyer.

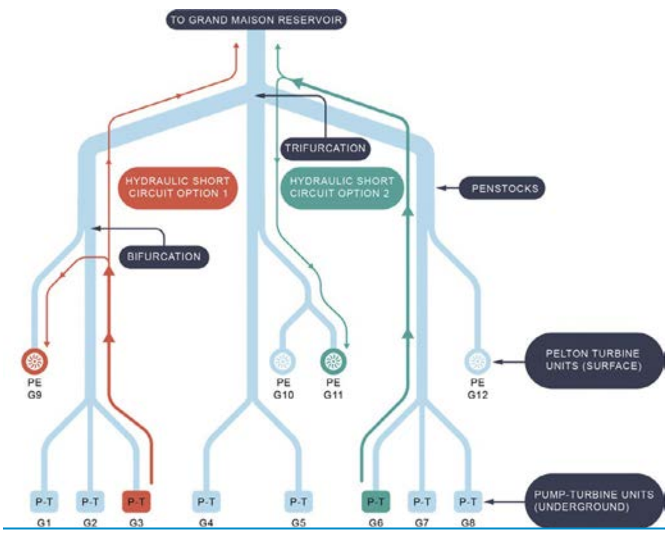


Figure 4 | Grand Maison PSP scheme of the waterways with the three bifurcations and the trifurcation as well as the flow paths for HSC Option 1 (orange) and HSC Option 2 (green blue). Infographic: Steve Sawyer.

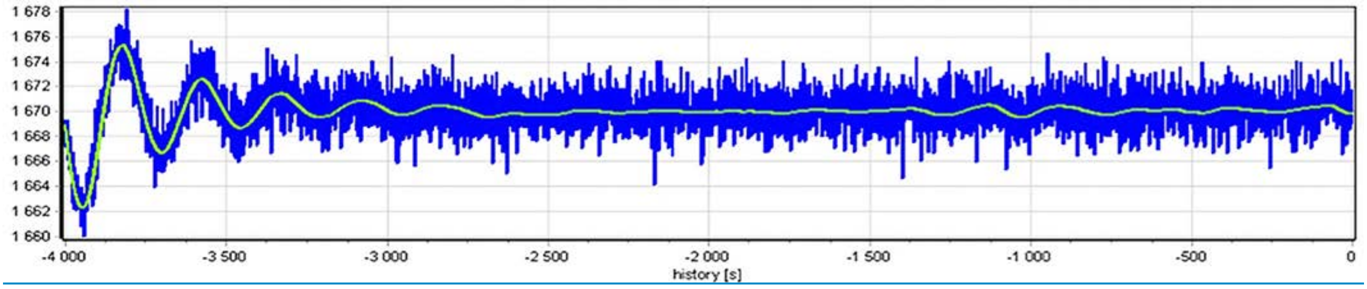


Figure 5 | Time history of the surge chamber level elevation (m) after a pump start up at -4'000 s. In blue measurements, in green Grand Maison HYDRO-CLONE® Digital output.

must stack generating units to meet customer demand and grid balancing reserve requirements at the lowest cost. Therefore, generating units with the lowest marginal cost are dispatched first and others follow according to their cost merit order.

Thanks to the EDF in-house optimization tool, a daily generating program for each plant is produced with 48 time-windows. After 18 months of demonstration at the Grand Maison PSP, it was found that the HSC mode was used for 30% of the operation time. In fact, more than one hour out of two hours in pumping mode also provided EPS grid support services through HSC.

As logic commands, energy storage through pumping occurs during off-peak periods or when there is excess generation. However, providing grid support services requires dispatchable generation to remain online, typically from gas fired power plants, although it may not be necessary for bulk power provision. Therefore, one of the direct consequences of the HSC mode availability is a reduction of gas fired power plant operation during off-peak periods since the power adjustment or grid support can be provided directly by the Grand Maison PSP at the energy storage point. Through predictive simulation, it is expected that operating the Grand Maison four Pelton turbines in HSC mode would reduce the global EDF CO_2 emissions by 90,000 tons per year.

Conclusion and Outlook

The XFLEX HYDRO project objective to reach the technology readiness level TRL7 has been achieved for the Hydraulic Short Circuit mode of operation for Pump Storage Power plants. The smart combination of one hydroelectric unit pumping at fixed set point while the hydroelectric generating unit regulates the power to adjust the net pumping power supplied by the grid, yields a new 3rd operating mode capable of providing both FCR and aFRR services to the same level and dynamic range as if it were operating in regular turbine mode. Indeed, the successful rollout of the HSC mode at Grand Maison will support the French TSO needs of 600 MW FCR and 700 MW to 1,000 MW a FRR provisions.

Acknowledgement

The authors would like to thank the colleagues of the XFLEX HYDRO consortium for their help and commitment to make the project successful.

The Hydropower Extending Power System Flexibility (XFLEX HYDRO) project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 857832.

References

1 | XFLEX HYDRO Consortium, *"Deliverable D2.2: Business Use Cases for the Provision of Flexibility Services by Hydropower"*, XFLEX HYDRO Public Deliverable, July 5, 2021.

2 | XFLEX HYDRO Consortium, *"Deliverable D2.3: Identification of flexibility services and standardisation"*, XFLEX HYDRO Public Deliverable, March 20, 2023. Ancillary Services Matrix - Stage 2.

3 | M. Guittet, M. Capezzali, L. Gaudard, F. Romerio, F. Vuille and F. Avellan. *"Study of the drivers and asset management of pumped-storage power plants historical and geographical perspective"*, in Energy, vol. 111, p. 560–579, doi:10.1016/j.energy.2016.04.052, 2016.

4 | J. Decaix, J.L. Drommi, F. Avellan and C. Münch; *"CFD simulations of hydraulic short-circuits in junctions, application to the Grand Maison power plant"*, 31st IAHR Symposium on Hydraulic Machinery and Systems, Trondheim, France, June 26–July 1, 2022, Published by IOP Conference Series: Earth and Environmental Science, Vol. 1079 012106. https://dx.doi.org/10.1088/1755-1315/1079/1/012106.

5 | C. Landry, C. Nicolet, C. Badina, H. Pichon and J.L. Drommi; "Contribution for the roadmap of hydraulic short circuit implementation: Case of Grand-Maison pumped storage power plant", 31st IAHR Symposium on Hydraulic Machinery and Systems, Trondheim, France, June 26–July 1, 2022, Published by IOP Conference Series: Earth and Environmental Science, Vol. 1079 012107. https://dx.doi.org/10.1088/1755-1315/1079/1/012107.

Jean-Louis Drommi

Expert engineer at Electricité de France, Hydro Engineering Center. He deals with all electrical aspects of hydro projects both at design stage and maintenance. He has been working at Electricité de France since 1987. J-L Drommi was awarded an engineering degree in 1986 from the Ecole Nationale Supérieure d'Ingénieurs Electriciens de Grenoble. He also has an advanced diploma in automation and signal processing. He is senior member of IEEE and author of several papers in the electrical and hydro field. He is member of CIGRE. He also currently leads EDF involvement in the XFLEX Hydro initiative funded by the EU.

François Avellan

Prof. François Avellan, Eng. Dr., EPFL emeritus professor, XFLEX HYDRO Scientific Advisor, graduated from Ecole nationale supérieure d'hydraulique, INP Grenoble, France, in 1977 and, in 1980, he got his engineering doctoral degree from University of Aix-Marseille II, France. Starting as a Research associate at EPFL in 1980, he became the director of the Laboratory for Hydraulic Machines from 1994 to 2020. Appointed as an Ordinary Professor in Hydraulic Machinery in 2003, he supervised 41 doctoral theses. SHF distinguished him with the "Grand Prix 2010 de l'hydrotechnique" and IEC acknowledged with the "IEC 1906 Award" his accomplishment as the TC4 working group maintenance team convenor of the IEC 60193 standards.

Grid-scale pumped hydro energy storage for the low countries

By Jeremy D. Bricker, Håkan Nilsson, Pal-Tore Selbo Storli, Daan P. K. Truijen, Jeroen D. M. de Kooning, Antonio Jarquin Laguna, Kristina Terheiden, Bernd Engel, Nils Goseberg and J. Roelof Moll

Penetration of intermittent renewable energy sources into the power grid requires large-scale energy storage to ensure grid stability. Pumped Hydro Energy Storage (PHES) is among the most mature, environmentally friendly, and economical energy storage technologies, but has traditionally only been feasible at sites with large natural topographic gradients. ALPHEUS addresses this by developing reversible pump-turbines efficient at low heads, that operate between an enclosed inner basin (that functions as the upper or lower reservoir) and a shallow sea or lake.

In a global effort to reduce greenhouse gas emissions, renewables are now the second biggest contributor to the world-wide electricity mix, claiming a total share of 29% in 2020. Although hydropower takes the largest share within that mix of renewables, solar photovoltaics and wind generation have experienced steep average annual growth rates of 36.5% and 23%, respectively, since 1990. This trend towards an increase in intermittent generation, coupled with a reduction in spinning reserves, could undermine grid stability. To counteract these effects, grid-scale deployment of energy storage is indispensable[3].

Integration of renewable energy sources into power grids worldwide has led to a need for storage on multiple timescales to balance electricity supply with demand. Among the various types of energy storage in existence (batteries, compressed air, flywheels, molten salt, etc.), pumped hydro energy storage (PHES) is the most mature, and therefore accounts for about 90% of utility-scale energy storage globally[1], has among the highest energy storage on investment, and incurs the lowest energy capital cost[4].

PHES has several advantages, yet large head differences between reservoirs are typically required, rendering countries with lowland topography unsuitable. A competing technology, lithium-ion batteries have made rapid progress toward higher efficiency and lower initial costs, but their lifetime is much shorter and carbon footprint greater than PHES. For example, the Energy Storage on Investment (ESOI), which represents the ratio of total energy stored over a battery's lifetime to the energy required to fabricate the battery, is 32 for a lithium-ion battery, but over 700 for a PHES facility. Similarly, it has been shown[4] that the Energy Capital Cost (ECC) distributed over the lifetime of a lithium-ion battery ranges from $7.5-$104 per kWh-cycle, while the cost of PHES is $0.02-$1.5 per kWh-cycle, and the total ECC of Li-Ion is $600-$3,800/kWh, compared to PHES at $5-$100/kWh. The sustainability of PHES is due to its long lifetime (hundreds of years for the civil structures involved, compared to 10-20 years for battery systems) and the recyclability of materials involved (primarily steel and copper for electromechanical components, as opposed to the rare, depletable, and geopolitically sensitive materials needed for batteries).

Further advantages of PHES include suitability for long-term storage –since the only storage losses are seepage and evaporation– and quick availability due to short switch-on and switch-off times. With these factors ensuring a significant share within a heterogeneous pool of storage technologies, one major disadvantage of PHES has historically been its topographic constraints; non-mountainous regions are not yet developed with PHES to their potential. The Netherlands, Denmark, and other low countries do not have the natural topography needed for PHES, so utility-scale backup supplies here are almost exclusively fossil fuel (gas, coal, oil, or diesel) thermal power plants or HVDC cables connected to mountainous regions (such as the NorNed cable connecting the Netherlands to Norway). Therefore, development of PHES feasible for the low countries would be beneficial for the environment, the economy, and grid stability. Challenges to pumped hydro storage in the low countries include the lack of suitable Reversible Pump-Turbine (RPT) technology that can operate with high efficiency in both pump and turbine modes at low heads, the need for novel civil structures and construction techniques to generate the head difference and storage volume needed, ways to mitigate fish mortality, and unknown response of the greater power grid to such local, distributed energy storage. To solve these issues, ALPHEUS (an acronym for "Augmenting grid stability through Low-head Pumped Hydro Energy Utilization & Storage") is a collaboration of engineers and scientists from four disciplines: mechanical engineering, electrical engineering, civil engineering, and fish ecology. The ALPHEUS project is funded by the European Union's Horizon 2020 program (grant agreement 883553), and coordinated by the Delft University of Technology.

Traditional PHES uses Francis-type RPT's, which are efficient at medium to high heads. Kaplan-type RPT's have been applied for low-head applications, but suffer from low efficiency when pumping. Therefore, ALPHEUS is developing a novel RPT technology for high efficiency at low heads in both pump and turbine modes. In the mechanical engineering component of ALPHEUS, Chalmers University of Technology and Advanced Design Technology Ltd. (ADT) apply Computational Fluid Dynamics (CFD) to design a contra-rotating propeller RPT (CR-RPT). In particular, ADT has employed a 3D inverse design method, built into the TURBOdesign suite, to design both shaft-driven and rim-driven CR-RPTs at both prototype and model scales.

The initial shaft-driven 10 MW prototype design showed a hydraulic efficiency of about 90% at a head of approximately 10 m in both pump and turbine modes. Finite Element Analysis (FEA) was employed to guarantee that the machine can handle applied loads. A multi-objective design optimization procedure using CFD was employed, increasing the hydraulic efficiency of the shaft-driven design in model scale by ~2.6% in pump mode and ~1.1% in turbine mode. Rapid switching between pump and turbine modes may be necessary if the PHES facility is to be used for grid frequency regulation in addition to daily or longer term energy storage. Chalmers University of Technology has performed a thorough optimization study of start-up and shut-down sequences with the aims to minimize loads and maximize the lifetime of the shaft-driven CR-RPT machines[2]. Experimental tests of model-scale contra-rotating and positive displacement RPTs are conducted at Chalmers University of Technology and Technical University Braunschweig, making validation of CFD results possible. In addition, as a complementary technology, the Norwegian University of Science and Technology (NTNU) is developing a positive displacement RPT (similar to a screw or lobe compressor), with the goal of functioning as an RPT with large size but low rotational speed.

Ghent University and Uppsala University combine their expertise from wind energy and hydropower to develop a variable speed power takeoff (PTO) and control system for the pump-turbine concepts. The key aim is to reach a highly dynamic, yet efficient, PTO and control in order to maximize opportunities for grid support. A cascaded proportional integral derivative (PID) control architecture has been developed, which has three control parameters: the first and second runner speeds, and the inlet valve opening. This will be upgraded to a model predictive control architecture, where transient behavior will be predicted in a detailed conduit model to change the control parameters accordingly.

Figure 2 shows the PTO designs for the three different pump-turbine concepts[5]. In all three concepts, double rotor axial-flux permanent magnet synchronous machines (AF-PMSMs) are used. Due to the absence of a stator yoke, these machines with a high diameter-to-length ratio have a high efficiency and high-power density, both of which are indispensable in an energy storage system. To investigate how the dynamic control actions influence the fatigue of the PTO, a methodology using rainflow counting has been established. Finally, to validate the control architectures and AF-PMSM design, a dry-test setup is developed at Ghent University in which the behavior of the turbomachinery is mimicked by two dynamically controlled induction motors.

The ELENIA Institute at Technische Universität Braunschweig deals with the question of integrating the ALPHEUS PHES into the electrical grid. The major issues ELENIA faces are investigations into the electrical behaviour of the PHES in terms of a grid compliant and grid supportive manner. As the systems architecture is based on a full-scale converter coupling of the PTO including innovative turbine concepts, this has potential to contribute to the provision of several Ancillary Services. An appropriate converter control design for an ALPHEUS power plant has been laid out in compliance with all requirements for its operation at the EU power grid.

To investigate the dynamic behaviour of the PHES in particular, a surrogate model in the time-domain has been developed. The model offers the possibility to derive the behaviour of the PHES in an integrative manner. It includes both electrical components of the grid-side inverter (internal calculation and controllers, output filter section and transformer) as well as estimations on the dynamic behaviour of the PTO unit such as the turbine and valve section. All components are scalable to multiple megawatts of nominal power. The simulation is able to perform with small sample times enabling simulations in dynamic time domains. The developed surrogate model of the grid-side inverter therefore is capable of investigating the plant behaviour integratively by including preliminary machine side dynamics, as well as electrical components of the inverter topology itself and the grid connection. Based upon an assessment of the abilities of the plant, future results will enable a determination of the capability of the plant to serve as provider of Ancillary Services which allows evaluation of the response of the interconnected grid and electricity markets to decentralized energy storage in the low countries.

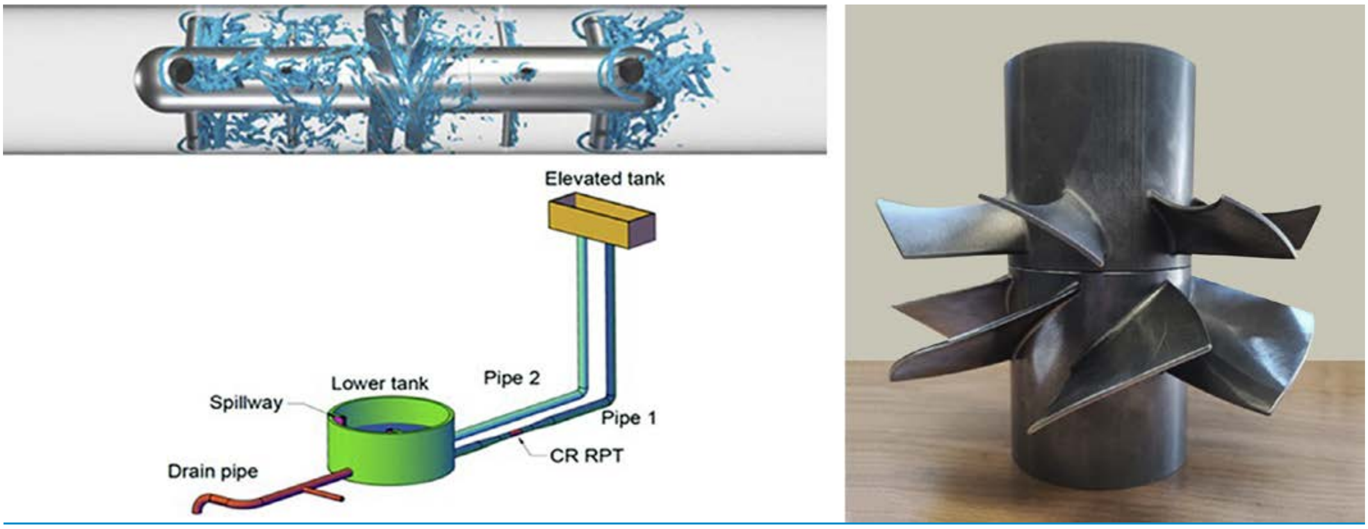


Figure 1 | *(upper left)* CFD of contra-rotating shaft-driven RPT in 30 kW model-scale experimental set-up. Iso-surfaces visualizing vortices in turbine mode. Flow is from left to right. *(lower left)* 3D view of the test setup for validation of the RPT and PD devices. *(Right)* 3D printed runners for the RPT laboratory model.

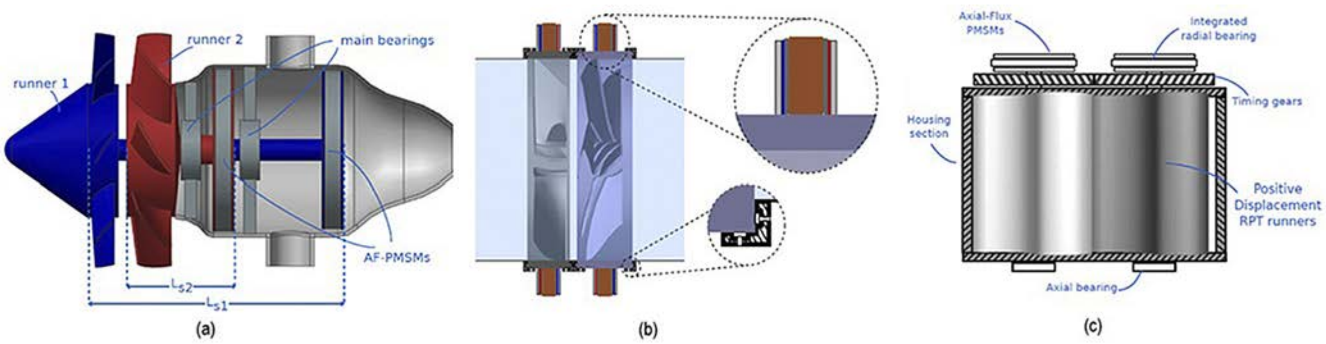


Figure 2 | Power Take-Offs (PTOs) for *a)* 10 MW shaft-driven contra-rotating reversible pump-turbine *b)* a 10 MW rim-driven contra-rotating reversible pump-turbine and *c)* a positive-displacement reversible pump-turbine.

In the civil engineering component of ALPHEUS, the University of Stuttgart, Delft University of Technology, IHE-Delft, Technische Universität Braunschweig, University of Tuscia, and the University of Pau and the Adour Region assess sites along the periphery of the North Sea for application of low head PHES. Conceptual designs of new and retrofit low head PHES basins are drafted, primarily relying on an inner reservoir that is either elevated or drawn down with respect to the sea (**Figure 3**). New structures encompass ring dikes in the North Sea, including Dutch and Belgian ideas such as Plan Lievense and the Princess Elisabeth energy island. Retrofits encompass concepts including the utilization of existing or proposed storm surge barriers or other structures, such as the Delta 21 Valmeer scheme. Comprehensive design of mechanical, electrical, and civil components allows costs of these schemes to be determined, and physical and economic risks assessed. As with all hydropower-related projects, a major concern is fish mortality, so University of Tuscia investigates the effectiveness and limitations of fish-friendly RPT's vs. fish screening technologies.

Figure 3 shows a conceptual design sketch of the dam. The design of the dam under coastal/offshore conditions is most constructible as a caisson structure buttressed by an embankment of fill material, with an underlying clay layer and curtain (not shown) providing waterproofing. The powerhouse structure will be built most efficiently as reinforced concrete structure either onsite using a cofferdam or with prefabricated caissons. Therefore, these methods are investigated in more detail to optimize the construction processes and hence investment costs.

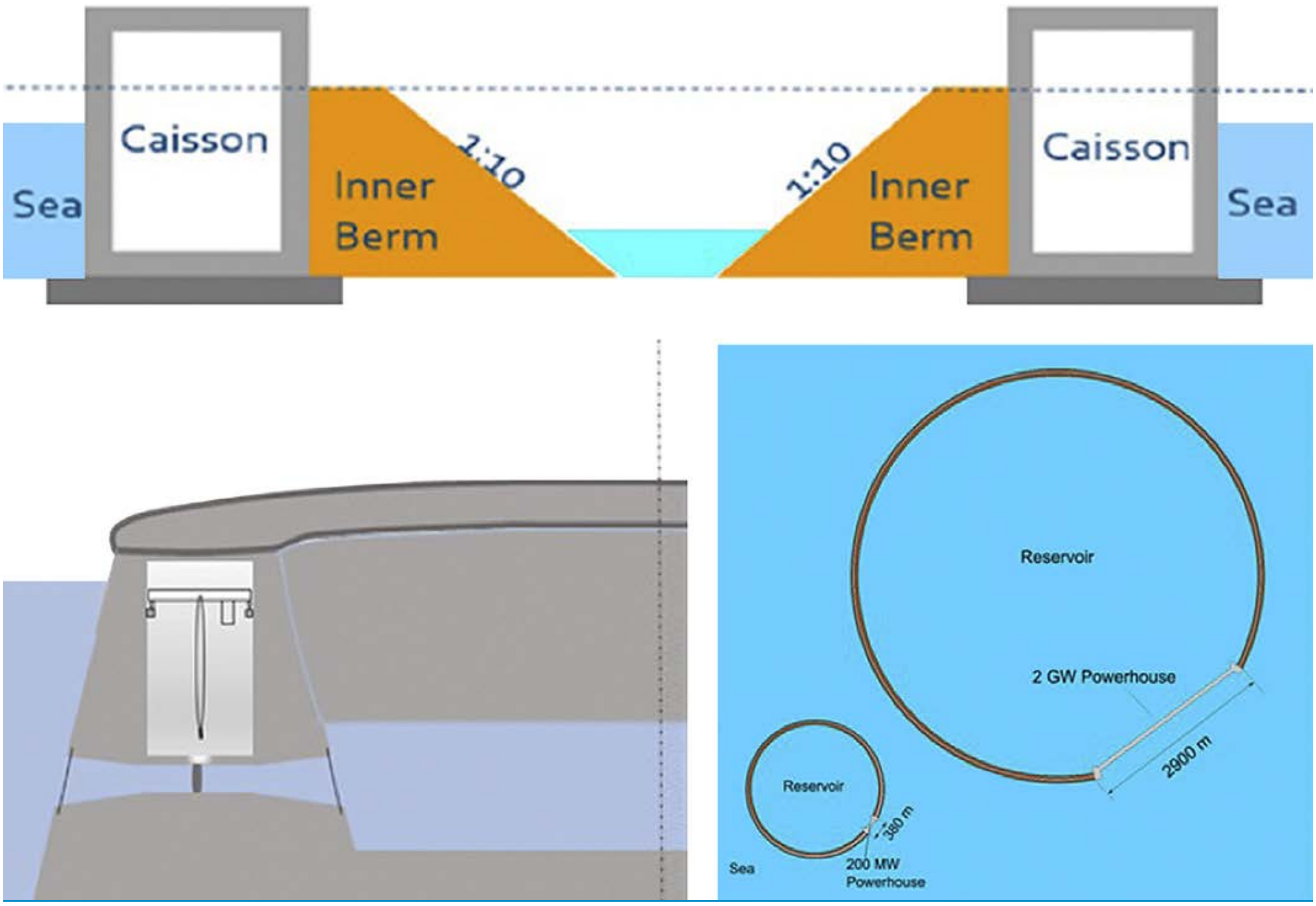


Figure 3 | Conceptual design sketch powerhouse/dam construction. The inner *(lower)* reservoir is pumped down below sea level to store energy, whereas seawater flows back in to generate energy. *(Upper)* Profile view of dam. *(Lower left)* Profile view of caisson powerhouse. *(Lower right)* Plan view of 2 GW and 20 GW capacity basins.

Furthermore, the powerhouse and overall plant design/size are optimized to be most compact. This is validated by operation simulations to optimize the RPT and to minimize material and construction volumes while guaranteeing certain grid services to maximize the revenue of the LH-PHES. In parallel, a risk assessment is performed on potential dam break scenarios and their impact on coastal areas. Fish screens are experimentally evaluated by the University of Tuscia in an outdoor flume at TU Delft to determine the stress on fishes caused by entrainment flows with fish screens indicated by measured hormone levels in fish.

To aid the integration of the various elements of the proposed system and examine its dynamic behavior and performance, a numerical model of the system has been developed in collaboration between TU Delft and Ghent University. It encompasses all relevant dynamic effects associated with the power conduit, the two contra-rotating runners, and the electric machines, while minimizing the computational resources required for simulations. This system model can be employed for a variety of purposes, such as assessing various control strategies, analyzing the impact of individual system components on the system's performance and dynamic behaviour in a potential storage facility, or assessing the system's ability to provide ancillary services to the grid while also determining its limitations.

The efforts of ALPHEUS come together in the construction of a complete 30 kW physical model of both the RPT and the PTO, for each RPT type (contra rotating and positive displacement). These are being tested at model scale under realistic head conditions in the hydraulics laboratory of Technische Universität Braunschweig. The tailored test setup, located at the laboratory of the Leichtweiß-Institute for Hydraulic Engineering and Water Resources, utilizes an elevated water tank whose water surface is at 10 m from the floor of the laboratory. The setup, as depicted in **Figure 1** is able to test both pump and turbine modes for the RPT. Pipe 2 provides water into the cylindrical tank so that the water can be pumped into the elevated tank without having a lowering of the water level within the lower tank. The runner was 3D printed in an aluminum alloy (**Figure 1**). Results from the model test will feed back into the mechanical and electrical engineering components of the project, which aim for the conceptual design of a 10 MW prototype RPT unit (for comparison, 10 MW is the capacity of a large modern wind turbine).

Finally, the ALPHEUS consortium recognizes the critical role that stakeholder communication and feedback play in the acceptance and success of low-head PHES. To this end, a questionnaire was distributed among stakeholders to gather stakeholder attitudes towards a low-head PHES technology and assess if stakeholders would put any redlines for its implementation. A second questionnaire will be distributed at a later stage to anticipate potential policy issues that the low-head PHES technology might face in the possible event of its implementation. Usually, the permitting process delays the implementation of renewable energy technologies and therefore the ALPHEUS project aims to pave the road to future bureaucratic processes prior to raised concerns of the public. To further facilitate stakeholder engagement, the ALPHEUS consortium is also organizing two stakeholder meetings. The first meeting has been held in March 2023, will have been involved the dissemination of the ALPHEUS project's work, a panel discussion between professionals, and audience participation. A following stakeholder meeting will be organized by the end of the project to disseminate the findings of the consortium.

Along the way, ALPHEUS is being monitored and kept on a useful track by an external expert advisory board consisting of Geisseler Law, EDF, The Blue Cluster, Tennet, HydroCoop, Rainpower, Artelia Group, and Prof. Anton Schleiss (EPFL/ ETIP HYDROPOWER). The completed model-scale RPT validation, together with the prototype-scale design, aims to bring low head PHES to a technical readiness level appropriate for prototype construction and grid connection. With the increasing penetration of intermittent renewable energy sources in the grid, such storage will benefit grid stability and security, as well as the economy and environment of the low countries.

Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 883553.

References

1 | Ansorena Ruiz, R., de Vilder, L. H., Prasasti, E. B., Aouad, M., De Luca, A., Geisseler, B., et. al (2022). Low-head pumped hydro storage: A review on civil structure designs, legal and environmental aspects to make its realization feasible in seawater. Renewable and Sustainable Energy Reviews, 160, 112281.

2 | Fahlbeck, J., Nilsson, H., & Salehi, S. (2023). Surrogate based optimisation of a pump mode startup sequence for a contra-rotating pump-turbine using a genetic algorithm and computational fluid dynamics. Journal of Energy Storage, 62, 106902.

3 | Hoffstaedt, J. P., Truijen, D. P. K., Fahlbeck, J., Gans, L. H. A., Qudaih, M., Laguna, A. J., ... Bricker, J. D. (2022). Low-head pumped hydro storage: A review of applicable technologies for design, grid integration, control and modelling. Renewable and Sustainable Energy Reviews, 158, 112119.

4 | Nikolaidis, P., & Poullikkas, A. (2018). Cost metrics of electrical energy storage technologies in potential power system operations. Sustainable Energy Technologies and Assessments, 25, 43-59.

5 | Truijen, D., De Kooning, J., Fauconnier, D., Vansompel, H., Sergeant, P., & Stockman, K. (2022). Axial Flux PMSM Power Take-Off for a Rim-Driven Contra-Rotating Pump-Turbine. In IEEE PES Asia-Pacific Power and Energy Engineering Conference. IEEE PES.

Jeremy D. Bricker, PhD, PE
Technical coordinator of ALPHEUS, he is Associate Professor (civil/hydraulic/coastal engineering) at the University of Michigan and Delft University of Technology.

Håkan Nilsson
Professor in Fluid Dynamics at Chalmers University of Technology, Sweden, specializes on development and validation of open source CFD for hydropower.

Pal-Tore Selbo Storli
Associate Professor in the Department of Energy and Process Engineering at the Norwegian University of Science and Technology.

Daan P. K. Truijen
MSc. in electrical engineering, is a PhD researcher at Ghent University and investigates the ALPHEUS power take-off and machine-side control architecture.

Jeroen D. M. De Kooning, PhD
Assistant professor in mechatronics at Ghent University, Belgium.

Antonio Jarquin Laguna, PhD
Assistant Professor, Faculty of Mechanical engineering at Delft University of Technology.

Kristina Terheiden, Dr.-Ing.
Head of the Hydraulic Structures and Hydropower group at Institute for Modelling Hydraulic and Environmental Systems of the University of Stuttgart.

Professor Bernd Engel
Executive director of the Institute for High Voltage Technology and Power Systems (ELENIA) at Technische Universitat Braunschweig.

Nils Goseberg
Professor at Technische Universität Braunschweig, heading the division of Hydromechanics, Coastal and Ocean Engineering of Leichtweiß-Institute for Hydraulic Engineering and Water Resources.

J. Roelof Moll
M Sc in Applied Mathematics 1981, is executive project coordinator of ALPHEUS and Head of section Hydraulic Structures and Flood Risk at TU Delft.

The Hydropower Flexibility Framework Tool: A Water-based Approach for Quantifying Hydropower Flexibility

By Francisco Kuljevan, Ali Camlibel, Mark Christian, Robert Entriken, Patrick March, Jake True and Paul Wolff

The resource mix across the globe is changing as renewable technologies become more cost-effective and as part of efforts to reduce the world's dependence on carbon-based generation technologies. Increasing amounts of variable renewable energy (VRE) resources, primarily wind and solar, are interconnecting with the grid. Worldwide pumped storage hydro currently provides regulation, spinning reserve, and approximately 96% of utility scale energy storage, and significant utility effort is focusing on increasing capacity at existing pumped storage facilities. Further, conventional hydroelectric power plants can, and often do, provide flexibility services for grid reliability and stability and for integrating VRE resources; they may have limited ability to store water and to provide regulation, and spinning reserve in addition to energy, such as for run-of-river plants.

The U. S. Department of Energy's (DOE's) Water Power Technologies Office (WPTO) under DE-EE0008941 is sponsoring the Electric Power Research Institute's (EPRI's) Hydropower Flexibility Framework (HFF) Project to develop a publicly available tool capable of integrating detailed hydropower plant characteristics with water availability through various Use Cases. This public tool uses an innovative, water-based methodology for analyzing and evaluating energy and flexibility services and a cloud-based calculation engine that co-optimizes unit-level dispatch for energy generation, regulation, and spinning reserve, subject to water availability. A hydropower plant's abilities to provide flexibility services, like regulation and other reserves, depends on its fuel (water availability and water-specific constraints), the plant-specific electrical and mechanical capabilities and constraints, and the environmental and regulatory constraints.

The HFF Tool's components are a plant model, an associated reservoir curve, and the minimum/environmental flow characteristics. The plant model includes optimized plant efficiency matrices, optimized regulation matrices, and a spin deployment probability to account for water use with spinning reserve commitments[2]. **Figure 1** shows optimized plant performance curves for a three-unit plant with varying amounts of regulation (i.e., regulation "swing" from the setpoint), using fixed dispatch.

Hydropower Flexibility Framework Applications

The HFF Tool employs multiple user-provided datasets, as outlined below, to perform the co-optimization and to provide the user with dispatches for various electricity market products, the revenue associated with these products, and the corresponding water flow schedules.

Data Requirements for the HFF Tool

- Unit Efficiency Characteristics
- Regulation Parameters (minimum and maximum swing for regulation)
- Reservoir and Tailwater Elevation Curves
- Minimum/Environmental Flow Requirements
- Initial Reservoir Elevation and Inflow Data
- Energy Market Price Data

By varying the data inputs, the user of the HFF Tool can explore a range of interesting topics, including assessing opportunities to support the dispatch decision process, provide valuable information when participating in electricity markets, assessing the potential benefits from participating in additional electricity markets, quantifying the impact of water passage regulations, understanding the impact of future hydrologic conditions, and estimating the benefits from future plant efficiency improvements. To aid in these assessments, the HFF Tool contains comparison capabilities that allow the user to view both an aggregated change in dispatch for various market products, total energy production, and revenue. While there are a host of different applications for the HFF Tool, the following seven Use Cases have been identified.

Improve the Dispatch Process

The first Use Case is an assessment of the decision-making process for hydropower dispatch to identify any opportunities for improvement. It is valuable to plant operators because any significant deviation between historic plant dispatch and the results from the HFF Tool may indicate areas where additional performance could potentially be gained, or additional tool calibration is needed. To perform this assessment, the HFF user uses historic reservoir inflows and market price data along with existing unit efficiency curves, minimum flow requirements, and reservoir curves. The HFF user can also examine improvements to multi-day dispatch planning by using expected reservoir inflows and expected market prices along with existing unit efficiency curves, minimum flow requirements, and reservoir curves. This Use Case allows the examination of current operations and also has the benefit of highlighting the value of increased accuracy of inflow and market forecasts.

Improve Existing Market Participation

The second Use Case focuses on improving future participation in electricity markets with which the plant owner is engaged. For this application, the user provides the HFF Tool with anticipated reservoir inflows and expected market prices along with known unit efficiency characteristics, constraints, and reservoir curves. The results of the HFF Tool may be integrating into existing market participation processes to enhance plant value and efficiency.

Assess Additional Market Engagement Benefit

The third Use Case explores the benefits from, and the implica-

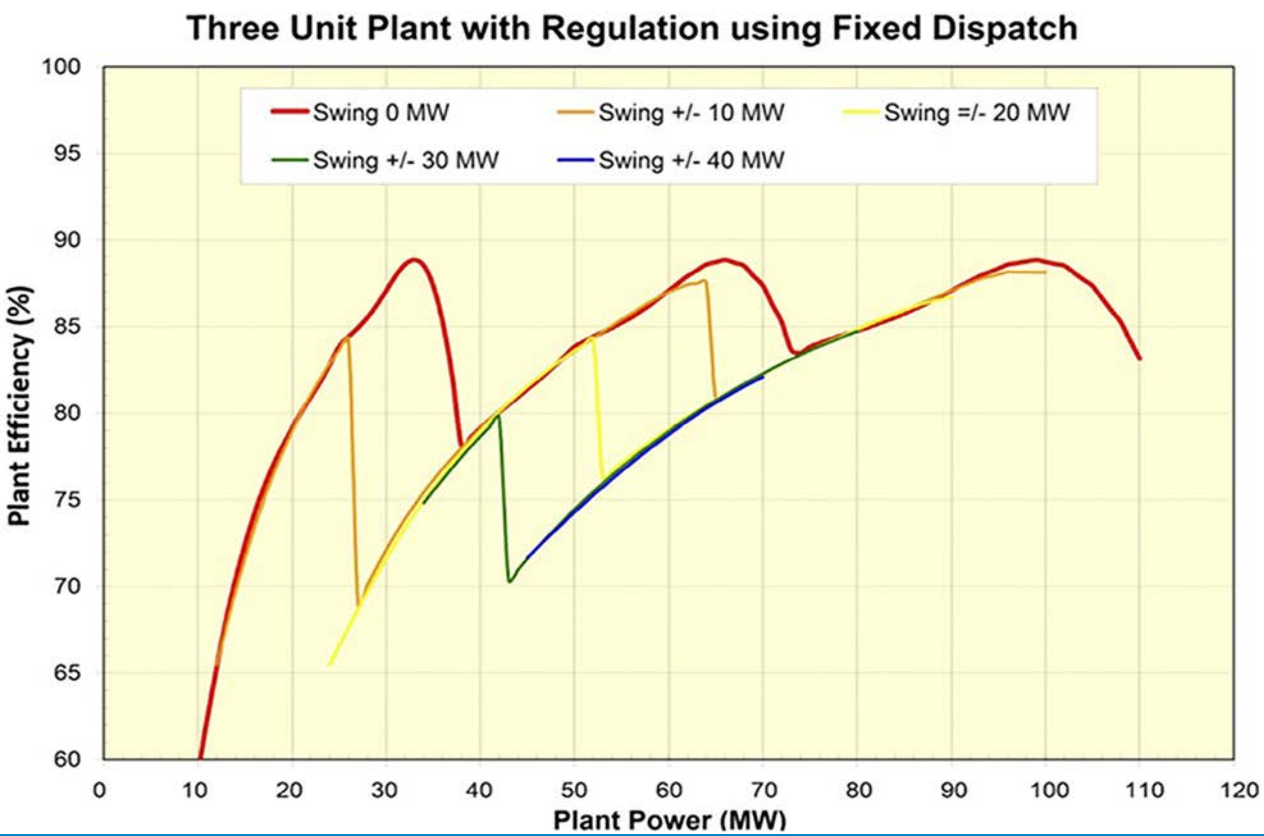


Figure 1 | Three-Unit Plant Performance Curves with Regulation using Fixed Dispatch.

tions of, engaging in additional flexibility services or of limiting engagement in them. Generally, there are four types of products offered by generation owners in a typical electricity market: energy, regulation, spinning reserve, and non-spinning reserve. As the share of variable wind and solar energy resources increases, the need for flexible resources, particularly those that can provide regulation and spinning reserve, also increases. However, predicting the impacts from market participation on overall revenue and on plant dynamics is challenging. Increased unit start-stops, off-design operation, and increased ramping has shown to have a negative impact on the remaining useful life of hydropower plant components[1]. To perform analyses within this Use Case, electricity market prices are gathered for representative locations and time periods and alternative market engagement scenarios are be developed and evaluated with the HFF Tool.

Calculate the Impact of Water Passage Requirements

As the understanding of social or environmental needs evolves, hydropower plants may be required to alter their minimum flow requirements. This stewardship of water resources is important but has potential implications on the ability of the hydropower plant to support the requirements of the electric grid. The fourth Use Case for the HFF Tool is focused on quantifying the impacts of evolving minimum flow requirements. For this Use Case, the user enters the existing minimum flow requirements in one simulation and the modified minimum flow requirements in another simulation using the same representative market price signals and water inflows. Analyses using the HFF Tool provide a comparison of the scenarios in terms of revenue, energy generation, and flexibility services (i.e., regulation and spinning reserve) to support the grid.

Evaluate the Impact of Future Hydrologic Conditions

The fifth Use Case estimates the impact of climate change on a hydropower plant's ability to provide grid flexibility services. The user performs a simulation with the HFF Tool using existing hydrologic conditions and then performs additional simulations using predicted stream flows, based on varying climate scenarios. The ability of the HFF Tool to assess numerous simulations is valuable, because the Tool can quickly produce results for numerous climatological scenarios. Such scenarios may include different Representative Concentration Pathways for varying levels of greenhouse gases in climate scenarios, different General Circulation Models used to predict large scale climatological effects, and different downscaling methodologies which take large-scale model results and convert them into local effects.

Assess the Flexibility Potential for Non-Powered Dams and Greenfield Development

While recent development of new domestic hydropower has been limited, there is significant potential for both non-powered dam (NPD) conversion and for new site development (Greenfield). Assessments from Oak Ridge National Laboratory have estimated the potential for new development at 12 GW for NPD and at 84.7 GW for new sites[3, 4]. The sixth Use Case focuses on quantifying the potential role that new hydropower could have in providing flexibility services, where the user enters data from a representative market prices, reservoir inflows based on stream gauge data, minimum flow obligations based on other facilities within the same basin or other prior knowledge, and reservoir elevation curves based on the existing asset for NPDs or planned inundation levels for a greenfield development. This Use Case serves as a valuable screening tool for site developers interested in quickly assessing the viability of a new development and the role that the new development could play in supporting the grid.

Predict the Flexibility Benefits from Efficiency Improvements

The seventh Use Case assesses the impacts of improvements to unit efficiency may have on hydropower plant grid support and value. The user performs one simulation using existing plant efficiency characteristics with a representative set of reservoir inflows and market signals and then performs an additional simulation using predicted plant efficiency using the same inflows and market signals. These results help improve predictions of the impact of system upgrades by including both energy and flexibility services. This application of the HFF Tool is particularly valuable as the hydropower industry continues to age, grid requirements for flexibility increase, and the Federal government is providing support for improvements to hydropower plant efficiencies.

Getting Involved

The HFF Tool will be launched online in the Summer of 2023, and it will be available to qualified users. Users of the HFF Tool will be required to register for accounts, users' data will be secured, and no secondary uses of the data will be allowed. The authors are highlighting the performance and use of the HFF Tool in a variety of hydropower community venues, including engagement with a Technical Review Committee, presentations to individual organizations, industry case studies, and industry conferences. If you are interested in using the HFF Tool, please contact Dr Mark Christian at mchristian@epri.com.

Acknowledgements

This project is supported by the Department of Energy's Water Power Technologies Office under Contract DE-EE0008941.

References

1 | EPRI, Flexible Operation of Hydropower Plants, Palo Alto, California: Electric Power Research Institute, Report No. 3002011185, May 2017.

2 | EPRI, Modeling Conventional Hydropower Plants to Duplicate Pumped Storage Hydro Operation, Palo Alto, California: Electric Power Research Institute, Report No. 3002019160, December 2020.

3 | Hadjerioua, B., Wei, Y., & Kao, S. (2012). An Assessment of Energy Potential at Non-Powered Dams in the United States. Washington: U.S. Department of Energy.

4 | Kao, S., McManamay, R., Steward, K., Samu, N., Hadjerioua, B., DeNeale, S.,..., Smith, B. (2014). New Stream-Reach Development: A Comprehensive Assessment of Hydropower Energy Potential in the United States. Washington : U.S. Department of Energy.

Francisco Kuljevan
Project Manager for Renewable Energy Research at EPRI. Leads the Hydropower Generation Program, which focuses on research for conventional and pumped storage hydropower asset management, performance and valuation optimization, technology development, and environmental challenges.

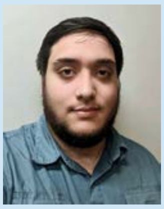
Dr Mark Christian
Technical Leader at the EPRI and specializes in systems analysis and modernization of conventional hydropower as well as project engagement in the Marine Renewable Energy sector.

Robert Entriken
Technical Executive for the Transmission Operations and Planning research program at the Electric Power Research Institute (EPRI). He manages projects addressing power system transformation and grid integration issues.

Patrick March
President and Principal Consultant for Hydro Performance Processes Inc. He has worked in the electric power industry since 1972, including work with the Tennessee Valley Authority's Engineering Laboratory from 1978-2005.

Dr Paul Wolff
Worked in the electric power industry including the Tennessee Valley Authority's Engineering Laboratory, work as an independent consultant since 2000. Paul has created spreadsheet-based computation engines that automate model creation for analyses of complex power plant processes.

Jake True
Senior Software Developer at EPRI. He has written software for the electric power industry for 15 years, including Web, Mobile, and Desktop applications which are used throughout the industry.



Ali Camlibel
Graduated from Virginia Tech in 2019 and has been a software developer in the energy space since. He started his career off at Duke Energy where he supported teams revolving around unit commitment. He then moved to EPRI where he currently works in various teams across the generation and nuclear sectors.

Increasing operational flexibility of Francis low-head turbines for increased grid resiliency

By Lee Lenhard, Guillaume Rudelle and Arvind K. Tiwari

Electrical grid resiliency is a vital national interest which is why the United States Department of Energy funded a research program led by GE and Eagle Creek Renewable Energy to increase the operational flexibility of hydro power plants and to simulate the impact this increased flexibility would have on the grid during a significant loss of generation.

The main findings of the program were:

- Low-head Francis-driven hydro power plants are a major source of additional grid flexibility.
- The additional flexibility from these hydro power plants can provide critical frequency response with the same reactivity as a battery storage system during a power generation failure to avoid a black-out.

Program Background

GE (GE Renewable Energy and GE Research) and Eagle Creek Renewable Energy worked together on the United States Department of Energy funded research program – "Increasing Operational Flexibility of Francis Turbines at Low Head Sites, Through Analytical and Empirical solutions" (referred to as 'Operational Flexibility Program' throughout the remainder of this article).

The goal of the almost-three-year program was to demonstrate the untapped flexibility potential of the low-head Francis hydro-power fleet by extending the turbine operating range. Increased flexibility would enable low-head hydro power plants to generate power over a wider operating range, contributing to grid system resilience and reliability.

The Operational Flexibility Program had two components:

The first was the engineering studies to quantify the range extension potential at Eagle Creek's High Rock hydro power plant. The focus of this research program was low-head –defined by GE as less than 80 m– Francis-driven hydro power plants. Francis turbines are, by far, the most widely used hydropower turbine and low-head units, accounting for about two-thirds of the U.S. Francis-driven fleet.

The second was the effort to simulate the impact of additional flexibility from the wider operating range at High Rock on the Western Electricity Coordinating Council (WECC) frequency response during a "worst case scenario" of lost generation, and comparing it to the frequency response of 300 MW of battery energy storage.

Figure 1 | High Rock hydro power plant.

High Rock Hydro Power Plant Operating Range Extension

Eagle Creek Renewable Energy selected its High Rock hydro power plant in North Carolina, USA for GE Renewable Energy to conduct the studies to quantify the potential for operating range extension at the plant.

The High Rock hydro power plant has three Francis-driven turbine and generator units of 13 MW each, running under a 17 m head and was opened in 1927 (**Figure 1**). The plant was refurbished in 2020 and dissolved oxygen technology via air admission was deployed to ensure oxygen levels in downstream aquatic ecosystems are at optimal levels.

For Francis-driven hydro power plants, the key flexibility driver is the operating range. Traditionally, hydraulic turbines are designed for a best efficiency point with a limited range of operation. Operation outside of this zone can cause unsteady hydraulic phenomena such as cavitation or inter-blade vortices for example, which can damage or even crack the steel runner.

However, existing units can have their range of operation extended by either replacing the existing runner with a new one specifically designed to operate over a wide range, or by assessing the capabilities of the existing runner.

For the High Rock units, GE implemented a testing and monitoring program to understand the behavior of the runner during partial load operation.

Strain gauges were installed on the runner to obtain data on the stresses on the runner from operating at partial load. The main sources of excitations that were identified were the partial load rope and rotating stall, however, the effect of inter-blade vortices were negligible.

Using data obtained from the stain gauges to identify the operating point with the highest stresses, GE leveraged its latest dynamic numerical simulation tools to determine the root cause. The simulations showed rotation cells located in the air gap.

A second site test with strain gauges was done to try to capture the rotating cells at the runner inlet and torque fluctuation on the wicket gates during turbine operation. The site test confirmed the rotating stall signature. It also confirmed the positive impact of aeration on runner stress.

The next step was a scale model test at GE's hydraulic test laboratory in Grenoble, France. The model test focused on inter-blade stresses during partial rope at deep partial load. The test also provided further verification of the benefit of aeration.

In parallel to these trials, GE installed and operated a condition monitoring system onsite for several months to capture the appearance of any identified unsteady hydraulic phenomena. The last step was a mechanical damage evaluation with and without aeration and a risk analysis on components other than the runner (**Figure 2**).

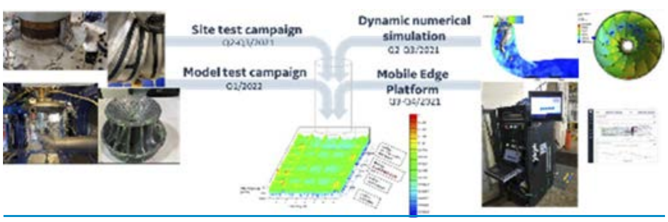


Figure 2 | Testing & monitoring program.

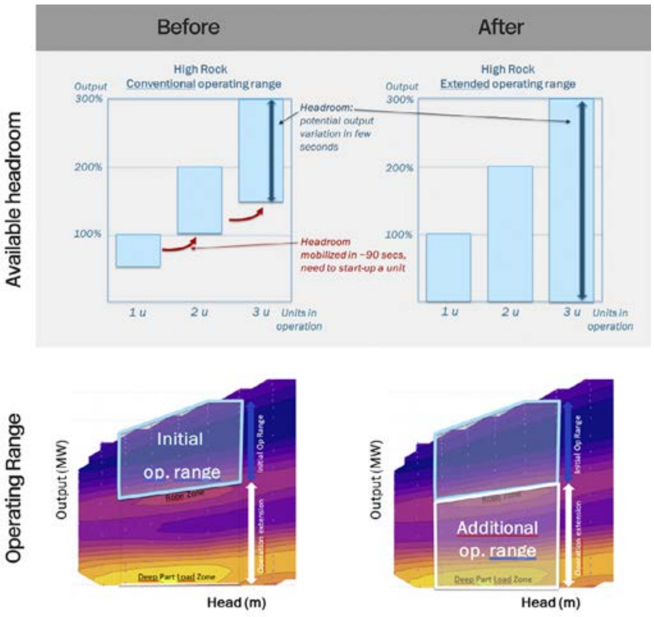


Figure 3 | Available headroom & operating range extension.

Based on the tests and analysis described above, GE was able to recommend an operation range extension with aeration that would not be damaging to the machine (**Figure 3**).

As previously mentioned, High Rock uses GE's Dissolved Oxygen runner which includes an inter-blade hydrofoil that introduces air at the leading edge of the blade, providing a wider distribution of air. GE's Dissolved Oxygen runner not only provides environmental benefits, it also decreases unsteady hydraulic phenomena.

The aeration capability of GE's Dissolved Oxygen runner coupled with results of the site and model tests led to a massive operation range increase from 50 to 100% load to 0 to 100% load.

Impact on WECC Frequency Response with More Flexible Francis Units

The impact of additional flexibility on the grid was simulated through the grid frequency response to a reference disturbance. This frequency response was calculated with and without the extended flexibility capabilities of the low-head hydropower fleet for a clear comparison. For purposes of this simulation, the Western Electricity Coordinating Council (WECC) was used, leveraging the models developed by GE in a previous DOE project entitled, "Value and Role of Pumped Storage Hydro under High Variable Renewables", completed in 2021.

The loss of two Palo Verde nuclear power station units was the simulated disturbance selected to evaluate the impact of additional flexibility services from the low-head Francis turbine units. In this study, this disturbance represented a total instantaneous loss of 2,756 MW of generation.

Three cases were compared in this study: a base case, a Francis turbine case and a battery energy storage case. The power flows from the base case were unchanged in all cases. For the base case, GE used a low load, high wind and solar penetration case in which wind and solar resources (both utility and distributed) provided 50% of energy to the system on an annual basis. This case represents a light spring load condition with high wind and solar penetration in the WECC. The Base Case has 72.7 GW of wind and solar generation, which represents 72.7% of total system load. The high penetration of wind and solar energy imposes high stress from a frequency response perspective.

The Francis Turbine Case was developed to evaluate the impact of increased flexibility of low-head Francis turbine units. In this case, the low-head Francis Turbines with unit output higher than 20 MW are considered to be operated over an extended operating range (from 0 to 100% of load); the consequence is that the 89 low head Francis units that were offline in the Base Case are online with zero power output (Full-speed-no-load) or very low power output (deep partial load), and thus are ready to ramp-up if needed.

The Battery Energy Storage Case tested the effect of battery storage on grid frequency response. This case determined how many MW of batteries were needed in the WECC system to have the same frequency response performance as the Francis Turbine Case.

The results of the simulation showed that the increased flexibility of the low-head Francis fleet prevents a massive drop of the WECC grid frequency below the first stage of WECC frequency load shedding, avoiding curtailment and blackout risk while, at the same time increasing grid inertia which also increases grid frequency response performance (**Figure 4**).

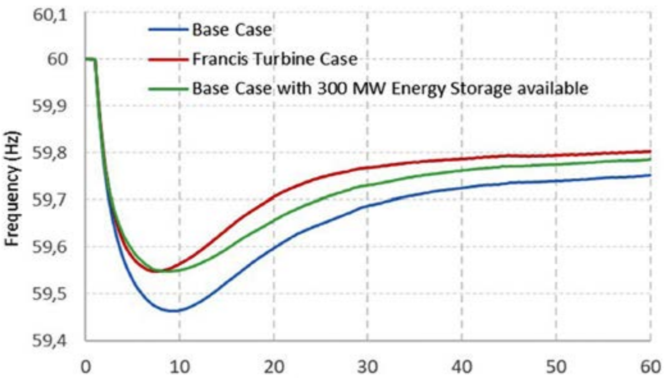


Figure 4 | Frequency response time (seconds).

In comparison with battery energy storage that can also offer frequency response, a fully flexible low-head Francis fleet offers:

- The same performance in terms of frequency nadir as 300 MW of battery energy storage
- Better performance in terms of settling frequency than 400 MW of battery energy storage. This is due to the sustainable power output from the Francis Turbine units. In contrast, the power output from battery energy storage tends to act fast but it quickly reaches its maximum output.
- Lower rate of change frequency (ROCOF) than 300 MW of battery energy storage
- At the end of simulation, the Francis Turbine Case still had plenty headroom left from the selected 100 Francis turbine units - 6289 MW (8166 MW - 1877 MW). This headroom can be used for other grid enhancement, e.g. AGC dispatch etc.

The Low head Francis fleet with extended flexibility offers gradual and sustained response to support the grid frequency. It also continues to offer large quantities of energy production and inertia.

Conclusion

The research program led by GE and Eagle Creek Renewable Energy and funded by the DOE has shown that the operational flexibility of hydropower plants can be increased by leveraging untapped headroom and that this additional flexibility can prevent blackouts by providing highly reactive frequency response during a power generation failure. Potential operating range extension can be assessed case by case on existing sites and maximized with a new runner design and adequate air admission, such as the case with the High Rock hydro powerplant where the headroom was doubled.

In addition to its environmental benefits, GE's innovative Dissolved Oxygen runner is a key asset in increasing operating range because of its air admission capabilities.

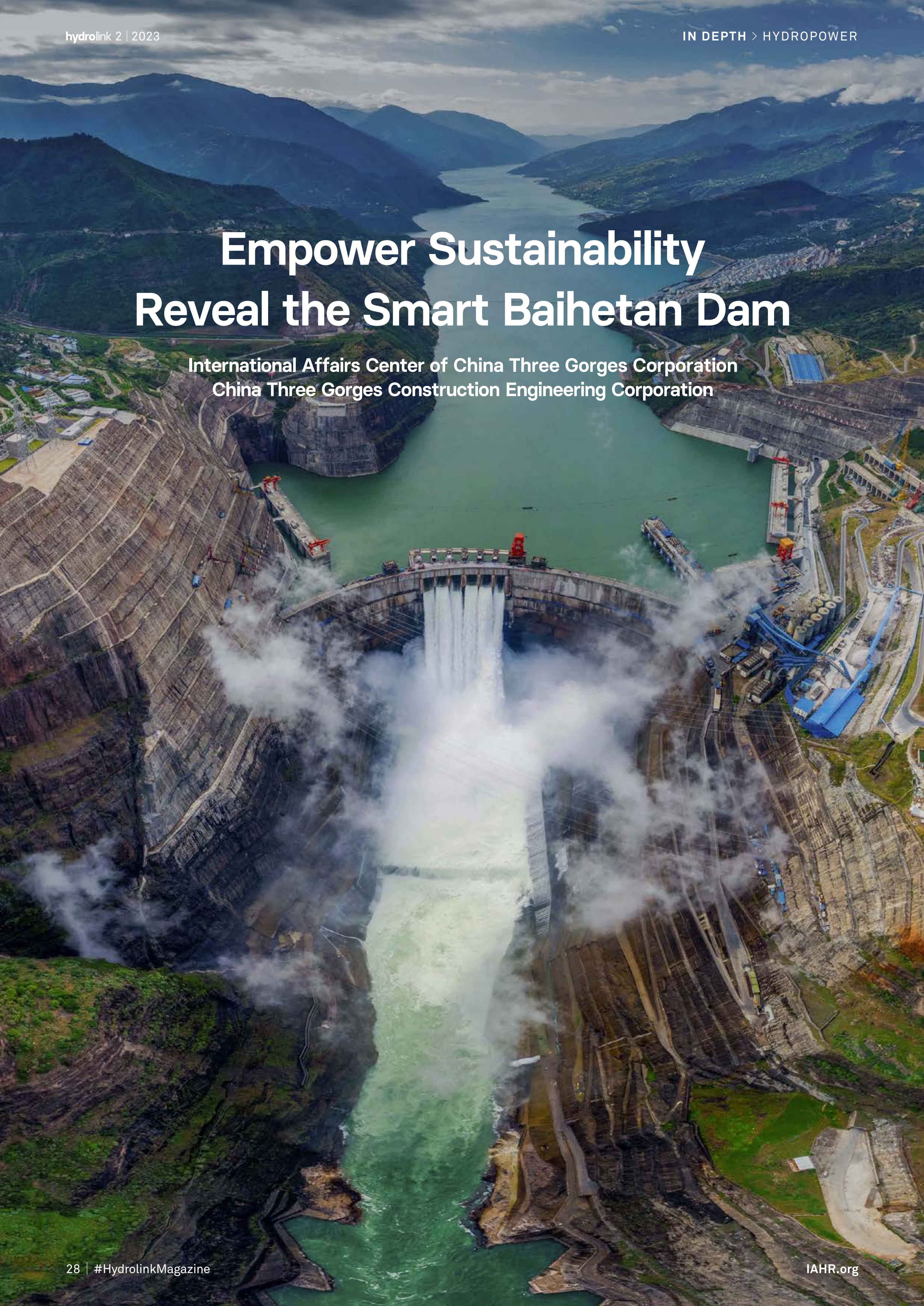
Lee Lenhard
Lee Lenhard is the Senior Product Manager for Large Hydro at GE Hydro Power. During his 12-year career at GE he has worked in a number of capacities, including communication, marketing and product manager. Prior to GE, Lee worked in the technology industry both in France and the United States. Lee holds a Bachelor of Arts degree from the University of Colorado at Boulder.

Guillaume Rudelle
GE Hydro Power-Senior product manager. He started as product manager for the small hydro product range, and then integrated the Technology Centre to manage various programs of new product introductions. Guillaume is leading the GE Hydro's efforts for both XFLEX-HYDRO and DE-EE0008942 projects, two major ongoing projects focused on developing and demonstrating solutions for flexibility increase of hydropower. Guillaume graduated in applied mathematics from the National Institute of Applied Sciences in Toulouse and in Innovation Management from the Grenoble Management School (France).

Arvind K. Tiwari
Arvind joined GE Research in 2003 with a focus on Electrical Machines and M&D. He led Electric Power lab at GE Research during 2009 – 2017. Arvind has been instrumental in maturing multiple technologies from ideation to product, such as Hybrids Renewable System and industrial machines M&D. He is currently leading electrification mission focused on Grid and Renewables. Prior to role at GE, he served at IIT, BHU, India during 1998-2003. Arvind has a distinguished academic record with patents, publications and co-authored a book. He earned his B. Tech, M. Tech., and Ph.D. from India.

Empower Sustainability Reveal the Smart Baihetan Dam

International Affairs Center of China Three Gorges Corporation
China Three Gorges Construction Engineering Corporation



The Baihetan Hydropower Station, an investment and construction endeavor undertaken by China Three Gorges Corporation (CTG), currently stands as the world's second-largest hydropower project, characterized by its unparalleled technical complexity. It serves as the backbone of power supply in China's west-to-east power transmission project and is an essential component of the flood control system in the Yangtze River Basin. During the construction process, many world-class challenges were over-come, leading to the establishment of several unprecedented records. Notably, the Baihetan hydropower station proudly boasts the world's most substantial single-unit million-kilowatt generating capacity, achieved through entirely independent research, design, manufacturing, and installation processes carried out within China. This marks a significant breakthrough in China's high-end equipment manufacturing, meaning that China has entered the "uncharted territory" of hydropower construction.

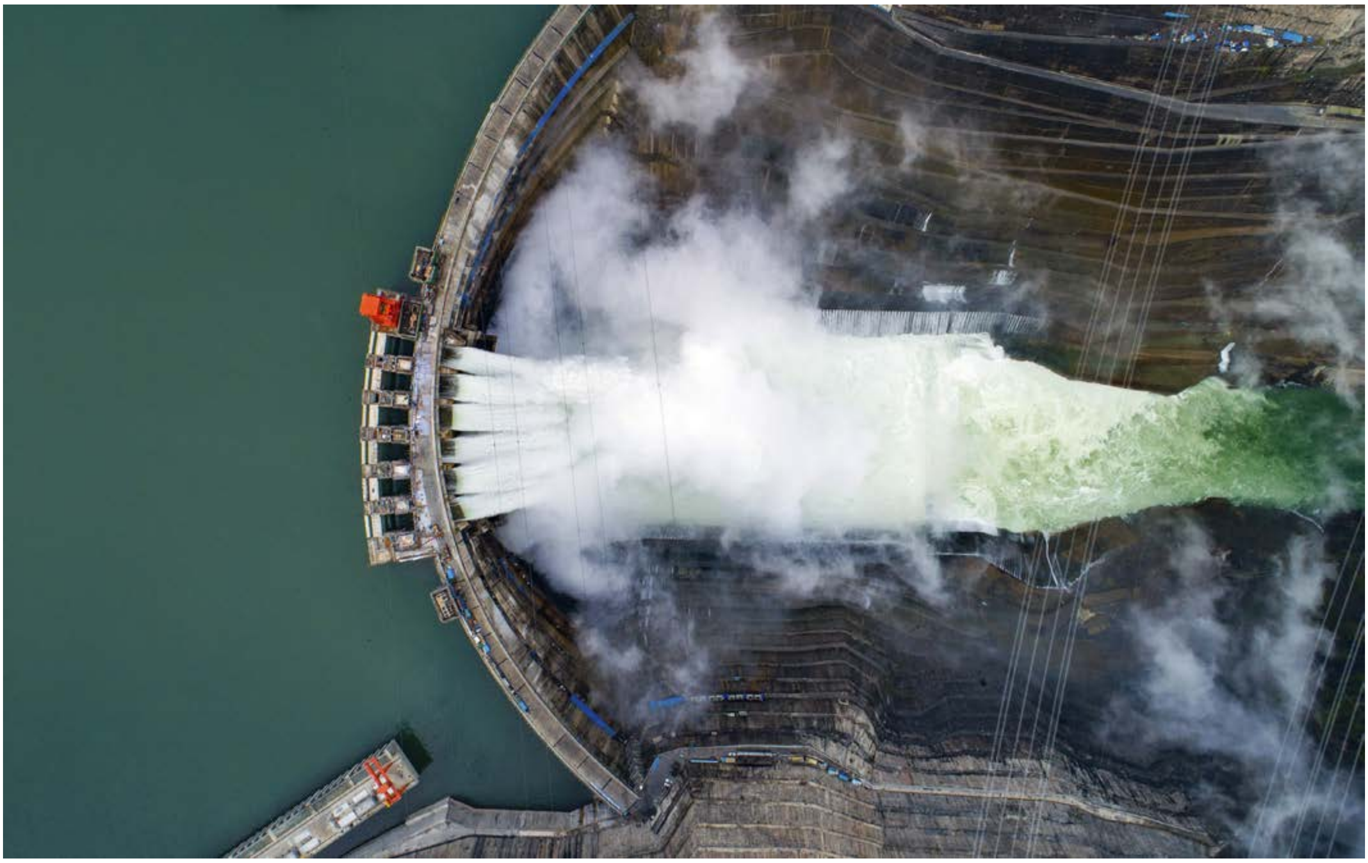
Innovation: Intelligent Construction of "Seamless Dam"

The Baihetan hydropower station is located on the Jinsha River (the upper reaches of Yangtze River), in an area characterized by a typical hot and dry valley climate with distinct dry and rainy seasons. Throughout the year, there are frequent high winds, and during the extreme summer months, temperatures can exceed 42 degrees Celsius. In the winter, temperatures drop sharply and frequently. The complex and dynamic climatic conditions pose unprecedented challenges for temperature control and cracking prevention of large-volume concrete.

In response to these challenges, CTG has been pursuing break-throughs in materials and technology. It is noticeable that the entire dam of the Baihetan project incorporates a cutting-edge, specially developed low-heat silicate cement[1,2]. This type of cement has the characteristic of low hydration heat, which can effectively control the maximum temperature of concrete after pouring, facilitating temperature regulation and enhancing the concrete's resistance to cracking.

CTG achieved technology advancements by harnessing the synergistic collaboration between industries, universities, and research organizations, undertaking a comprehensive approach to intelligent construction. By delving into the realm of concrete temperature control theory, CTG has refined methodologies and executed dynamic on-site temperature regulation based on thorough simulations of the dam's entire lifecycle. Leveraging intelligent equipment, such as monitoring systems, spraying systems, and water circulation systems, CTG has successfully implemented innovative techniques and approaches. This meticulous orchestration of operations has led to precise temperature control throughout the construction process, culminating in the construction of a seamless dam.

To monitor the construction progress, internal temperature, stress levels, and environmental changes, an extensive network of tens of thousands of sensors was meticulously installed. Functioning akin to "neurons", these sensors are interconnected and linked to an intelligent construction information platform. This setup enables engineers to access real-time data on the status of the dam and conduct scientific studies and assessments promptly[3,4,5]. This intelligent engineering construction system realizes full-life cycle management with comprehensive perception, authentic analysis, real-time control, and continuous optimization. It assists engineers in making on-site decisions and help improve the project construction management.



Green Power: Emission Reduction Facilitates National Carbon Peak and Neutrality Goals

With an average annual power generation of 62.443 TWh, the Baihetan Hydropower Station is a pillar of China's west-to-east power transmission project. It surpasses other cascade hydropower stations along the lower reaches of the Jinsha River in terms of storage capacity and cascade efficiency, being the largest and most advantageous.. By utilizing its storage advantages through cascade dispatching, the power generation quality of the downstream power stations, including Xiluodu, Xiangjiaba, Three Gorges Project and Gezhouba is significantly improved. Each downstream cascade power station will be able to increase power generation by 2.43 TWh annually and 9.21 TWh during dry season.

The significant benefits of emission reduction from the Baihetan Hydropower Station perfectly complement its power generation capacity. After all its units are put into operation, under the condition of meeting the same power system demand, the station has the potential to save about 19.68 million tons of standard coal (equivalent to about 27.56 million tons of raw coal) each year and reduce emissions by 51.6 million tons of carbon dioxide, 170,000 tons of sulfur dioxide, and about 150,000 tons of nitrogen oxides. Each kilowatt hour generated by the Baihetan hydropower plant contributes to the green development of the Yangtze River Economic Belt and bolsters the nation's efforts to reach its carbon neutrality goals.

Flood Prevention: Combined Barrier against Extreme Weather

The Baihetan Hydropower Station serves as a vital shield against flooding, protecting the people along the Yangtze River. As an important component of the Yangtze River Basin flood control system, its flood control capacity amounts to 7.5 billion cubic meters, equivalent to the combined capacity of the other three cascade reservoirs in the lower reaches of the Jinsha River. By coordinating with these downstream cascade reservoirs in the lower reaches of Jinsha River, the flood control capacity for Yibin, Luzhou, Chongqing and other cities along the Chuan River (a section of Yangtze River) has been further improved. In addition, it efficiently mitigates the disastrous flood and flood diversion losses in the middle and lower reaches of the Yangtze River by supporting the dispatching of the Three Gorges reservoir.

Eco-priority: Leading Green Development Across the Board

The Baihetan Hydropower Station exemplifies a steadfast commitment to the harmonious coexistence of humanity and nature, actively engaging in ecological restoration and safeguarding species diversity. In terms of aquatic ecological protection, various fish protection measures such as multi-level water intake facility, fish collection and transportation system, ecological restoration of fish habitats, and stock enhancement station have been built, collected about 15,000 fish annually and achieved an ecological balance of fish from upstream and downstream. In terms of terrestrial ecological protection, the station has taken significant steps to protect and nurture the environment: 345 old trees have been protected, 57 old trees have been trans-planted in the submerged area, 162 endemic and rare plants have been cultivated, and a 140,000 m^2 botanical garden has been built. The cumulative re-vegetated area exceeds 500,000 m^2, and the total area of cut-over land restored in adjacent area reaches 402 hectares, creating a good habitat for wildlife and presenting a beautiful scene of lucid waters and lush mountains.

References

1 | Minglun Sun, Zeqing Hu, *et al.* Application of low heat Portland cement in spillway tunnel engineering(Chinese)[J]. Yangtze River, 2011, 42(10): 157-160.

2 | Xiaofeng Gao, Min Du, Chunfeng Liu, *et al.* Experimental study on fracture performance of low-heat cement concrete in Baihetan Dam(Chinese)[J]. Journal of Zhejiang University of Technology, 2021(6): 664-668.

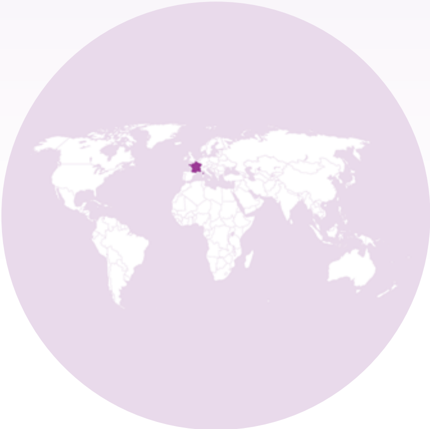
3 | Ming Li, Peng Lin, Yaosheng Tan, *et al.* An ANN-Based Short-Term Temperature Forecast Model for Mass Concrete Cooling Control[J]. Tsinghua Science and Technology, 2023, 28(6): 511-524.

4 | Peng Lin, Ming Li, Ke Liu, Zongli Yang, *et al.* Study on adaptive intelligent cooling strategy for low-heat cement RCC[J]. Journal of Hydraulic Engineering, 2022, 53(9):1028-1038.

5 | Peng Lin, Zeyu Ning, Ming Li, Qixiang Fan, Zhilin Wang, *et al.* Study on prototype intelligent control test of cooling pipeline for a super-high arch dam[J]. Journal of Hydraulic Engineering, 2021, 52(7):819-828.

FAMOUS WOMEN IN FLUID MECHANICS

The IAHR task force on Strengthening Gender Equity intends to raise the profile and visibility of women who made major contributions to hydraulics.



$$E_K = \frac{3}{2} k_B T$$

Laure Saint-Raymond
1975, France

Isabelle Gallagher
1973, France

These two brilliant mathematicians were educated in two of the most prestigious French academic institutes, *Ecole Normale Supérieure de Lyon* and *Ecole Polytechnique,* respectively.
They established, both independently and by working together, profound results on two large subdomains of fluid mechanics:
1 | The transition from molecular dynamics to continuous fluids, investigating how the Boltzmann equation leads to the Euler and Navier–Stokes equations in a large set of colliding atoms or molecules.
2 | The theory of geophysical flows accounting for the Earth's rotation, particularly the Poincaré waves, the Rossby waves and internal waves due to density stratification. In addition to their research and teaching activities, both arerecognized for their skills and investment in science popularisation and dissemination to the public.

Laure Saint-Raymond is now a professor at the *Institut des Hautes Etudes Scientifiques.* She has received many awards including the Fermat Prize and the Bôcher Prize of the American Mathematical Society and was elected to the French Academy of Sciences (2013) and to the European Academy of Sciences (2017).

Isabelle Gallagher is now head of the *Fondation Sciences Mathématiques de Paris,* after two years as a department head at *Ecole Normale Supérieure de Paris.* She has been awarded many times, including the 2023 Erwin Schrodinger Institute Medal.

Source: Wikipedia.

Prince Sultan Bin Abdulaziz
International Prize for Water

Recognizing Innovation

Invitation for Nominations

11th Award (2024)

Nominations open online until 31 December 2023

www.psipw.org
e-mail: info@psipw.org