Winning the productivity race in hydropower

Time for agile operational innovation and a digital asset management mindset

September 2021

Arthur D Little

Content

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We would like to acknowledge all those who contributed in the review of this Report, the development of benchmarking in different hydropower plants globally, and previous consultancy for this Report, especially: Bernd Schreiber, Federico Torretta, Santiago Jaramillo, and Agustín Compagnucci. We would also like to thank those in Arthur D. Little's Energy & Utilities practice who collaborated with us as well as the executives responsible for O&M of the hydropower companies that participated in prior studies.

Executive summary

There's a growing need to adapt and prepare the conventional hydropower operating model for the global energy transition. This urgently calls on hydropower operators to move toward a digital transformation process that requires agile operational innovation and a digital asset management mindset. Although some hydropower operators have begun implementing digital solutions, many remain locked in the conventional operating model. Furthermore, technological disruption from efficient renewable energy alternatives, changing dynamics from regulators and industry players, and a greater unpredictability of water supply are all critical uncertainty drivers. Growing market and operational uncertainty is primarily driven by increased competition, the need to maximize asset productivity while sustaining a lean cost structure, increased climate change, growing pressure from regulators, and cultural change obstacles. In this Report, we address some actions hydropower operators can take to push through these challenges.

Digital operations solutions are opening a wide array of opportunities for cost efficiency and asset productivity. These technologies can strengthen management capabilities to confront myriad critical challenges in the hydro business and operational model. Within the application space of digital solutions for hydropower operations, we have distinguished some that hold great promise in terms of capacity to impact and accelerate the digital maturity of the traditional hydropower operational model. We have identified five digital initiatives that promise high ROI and a major improvement on key hydropower business levers, including enhancement in plant reliability and availability, minimization of the cost base of the generation baseload, and optimization of commercial and trading processes.

Prior to implementing solutions, it's important to first understand the positioning of the hydropower operator in terms of digital maturity within the hydropower operational value chain. Identifying key digital gaps is essential to building a sustainable and effective digital operational strategy. As shown in the Report, we have developed a digital maturity model for hydro operators that can provide a baseline for management to envision, plan, and execute its digital strategy. The maturity model covers four key stages that evolve from a conventional model to a final stage, where a fully automated operation is achieved and asset management reaches a holistic focus that integrates operational, financial, and risk management levers to business outcomes.

For hydropower operators to achieve a successful digital transformation, they must consider the following four key success factors: (1) well-defined digital strategy and ambition; (2) change management, agile mindset, and digital culture; (3) robust data governance; and (4) reliable and scalable cybersecurity capabilities, all of which are discussed fully in this Report.

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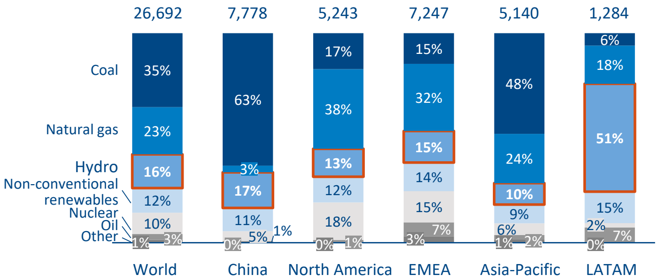
1. Navigating changing market dynamics in hydropower

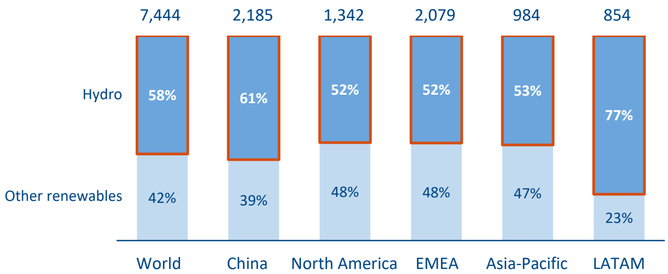
The ongoing transformation of the world's energy systems toward a decarbonized future is characterized by a disruptive force in technology, markets, and regulation. Hydropower, representing just 16% of global electricity generation (see Figure 1) and almost 60% of total renewable energy generation (see Figure 2), has all but disrupted itself. This 100-year-old technology has not seen major technological breakthroughs in the last decades.

Figure 1: Hydropower in global electricity generation: TWh – 2020



Source: BP Statistical Review of World Energy, 2021

Figure 2: Hydropower in global electricity generation from renewable sources: TWh – 2020



Source: BP Statistical Review of World Energy, 2021

The state of the hydropower game

Hydropower operators have, to say the least, been shy in pursuing technical and business model innovation due to: (1) alignment between growing cost pressure on baseload generation and lack of awareness of the digital dividend on hydropower operations; (2) high complexity and heterogeneity of most asset fleets, which appear to be an obstacle in reaching full digitization at scale; and (3) some adverse regulatory context that offsets incentives for digital investment primarily observed in highly concentrated markets or where state-owned companies are market leaders. Although some hydropower operators have begun implementing centralized and remote operations, or even some exploratory pilots of key digital solutions technologies, many remain locked in the conventional operating model, which is highly labor-intensive and driven by inefficient processes that become hurdles for maximizing productivity.

Technological disruption from ever more efficient renewable energy alternatives, changing dynamics from regulators and industry players that race to adjust to a more competitive and consumer-centered energy market, and a greater unpredictability of the water supply due to climate change are all critical uncertainty drivers for hydro performance. Thus, today's hydropower operators must innovate their conventional operating model and accelerate their digital transformation to confront these challenges. The ultimate test for best-in-class hydropower companies will be to navigate these changing market dynamics while assuring optimum asset productivity and operational efficiency.

2. Challenges in hydropower excellence

As a capital-intensive business model, hydropower operators must deliver high margins under the umbrella of growing market and operational uncertainty. The uncertainty is primarily driven by increased competition from other renewables, the need to maximize asset productivity while sustaining a lean operational cost structure, increasing climate change disturbances, growing pressure from regulators and public opinion to assure environmentally sustainable practices, and the obstacles in overcoming cultural changes when pursuing digital transformation. Below are some actions hydropower operators can take to push through these challenges:

- **Strengthen market competitiveness.** Renewable energy sources will increase their share within the energy matrix of most economies as technology improvements allow for a lower levelized cost of electricity, which increases their financial attractiveness for greenfield development. Growing participation in the energy matrix in addition to advancements in micro grid and cogeneration development will further put pressure on market prices. This scenario, in particular, will represent a significant challenge to medium- and small-scale hydro plants as they will have limited ability in their reservoir management to navigate the changing market dynamics.
- **Maximize asset productivity.** The aging factor of hydro fleets and the changing energy market will require management to seek an innovative operational model that extends the lifetime of the assets while at the same time assures high plant availability and reliability. The market will require plant operators to have greater flexibility in dispatch to assure revenue optimization, where innovative maintenance schemes should respond to minimize plant downtime. The aging of the hydro fleet will be particularly critical for North America, Europe, and Latin America, where average fleet age rounds over 50, 40, and 30 years old, respectively, according to the International Energy Agency. To assure an efficient allocation of CAPEX investments for refurbishment, management must rethink its approach to asset management.
- **Maintain lean O&M cost structure.** Given the changing energy market environment, the potential demand for higher infrastructure rehabilitation in older plants, and the need to extend asset lifetime, management will need to pursue a lean O&M cost structure that both shields the plant's profitability and strengthens its operational performance. Cost efficiency will require maintenance schemes to start leveraging digitalization and for plant operations to begin migrating to remote and autonomous models.
- **Confront climate change.** Increasing volatility and intensity of climate cycles are significantly impacting the water supply of most hydropower plants. Under this context of uncertainty, risks will rise across the hydro business model, since the energy allocation for commercial optimization will become more complex, the probability of infrastructure failure will increase, and an upward pressure of insurance premiums cost will be expected.
- **Strengthen sustainability.** Hydropower projects are under constant, growing pressure from regulators, communities, and shareholders to act toward the mitigation of environmental impact from hydro activities on surrounding ecosystems, the protection of drinking water resources, and the preservation of the economic livelihood of surrounding communities.
- **Promote digital-oriented culture.** The need to adapt and grow digital capabilities within hydropower organizations is a challenge in itself, especially for legacy plants and state-owned operators not amiable to change, either due to an aging workforce deep-seated in the traditional mechanic onsite operational mindset, or because of an ingrained bureaucratic organizational environment that comes into friction with any ideas of efficiency, let alone process optimization.

3. Digital capabilities and solutions for the hydropower operational model

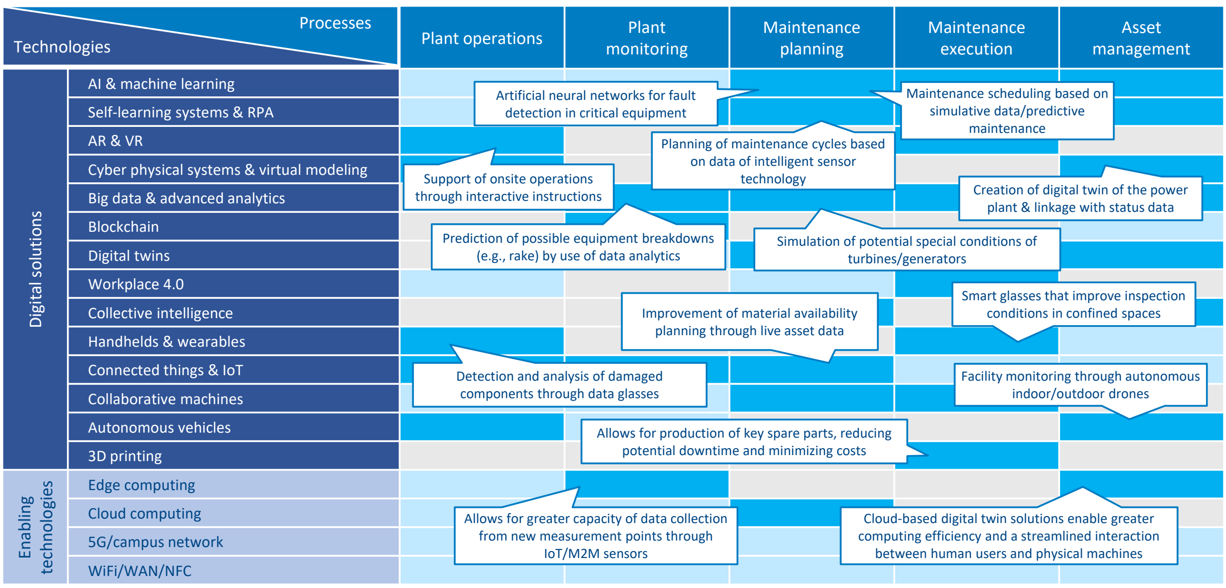
Digital operations solutions are opening a wide array of opportunities for cost efficiency and asset productivity in hydropower. The implementation of these technologies will strengthen management capabilities to confront the myriad critical challenges already affecting the hydro business and operational model. Innovative technologies like artificial AI, big data, and blockchain lay sizeable opportunities for operational efficiency across the hydropower value chain. At Arthur D. Little, we have identified over 150 different use cases that can enable hydro operators to achieve greater cost efficiency, optimize performance, and ultimately increased value for all stakeholders. To identify potential usage of these new digital solutions within the hydropower operational model, we developed a cross-grid identification scheme between key processes of the hydropower value chain and new technologies (see Figure 3).

The main scope of the application space of these new digital solutions is set at the operational processes of a running hydropower plant (excluding any greenfield or brownfield planning and building as well as plant decommissioning process).

As shown in Figure 3, key processes covered are: **plant operations** and **monitoring**, which involve the operational and surveillance procedures of key critical equipment, the decision process of energy dispatch, and the execution of the business strategy; **maintenance planning**, which encompasses the budgeting of materials, contractor support and other services, the structuring of maintenance schedules, and the design of maintenance guides and procedures; **maintenance execution**, which includes maintenance overhauls and all related activities that involve preventive and corrective actions on all equipment and plant-related facilitates; and the cross-sectional process of **asset management**, which involves the direction of operations, maintenance and secondary infrastructure oversight, as well as execution of overall risk management strategy and alignment with key business objectives.

The potential technologies are divided between **digital solutions** and **enabling technologies**. Digital solutions are the applicable software and hardware tools and systems that transform the process in question. For example, machine learning (ML) solutions allow hydropower operators to process and model vast amounts of operational data, which enables new predictive

Figure 3: Digital operations applications for hydropower operations



Source: Arthur D. Little analysis

Proven high impact for HPP operations   Exploratory application for HPP maintenance algorithms to predict with greater accuracy the fault occurrence of critical equipment. This helps in providing direction to the maintenance team in taking preventive measures before failure.

Digital enablers are technologies that allow the systems and equipment to function; specifically, these enablers will act as the functional layer of the entire digital ecosystem within the plant. For example, cloud technologies will be the core IT architecture that will support key technologies, such as big data solutions or the implementation of a digital twin, with significant computing efficiency that allows for higher productivity and minimum cost.

Within the application space of abundant digital solutions for hydropower operations, we have distinguished some that hold great promise in terms of their capacity to impact and accelerate the digital maturity of the traditional hydropower operational model. Through discussions with leading hydropower operators, we have identified five digital initiatives that promise a high ROI and a major improvement on key hydro business levers, including enhancement in plant reliability and availability, minimization of the cost base of the generation baseload, and optimization of commercial and trading processes. These five initiatives (see Figure 4) rank high in both feasibility and productivity impact:

1. **Advanced analytics and continuous monitoring to unlock predictive maintenance capabilities.** The increasing adoption of continuous monitoring solutions in power plant equipment has allowed for the capturing of massive volumes of information on a wide array of process and state variables; data once provided on a daily or even monthly basis is now obtained at minute-or second-based frequency. This rapid growth and accumulation of a vast amount of data give way to the development of predictive algorithms that anticipate with great accuracy the probability of machine failure, thus optimizing maintenance schemes that minimize machine intervention costs, increase personnel productivity, reduce plant downtime, and avoid corrective maintenance expenditures.

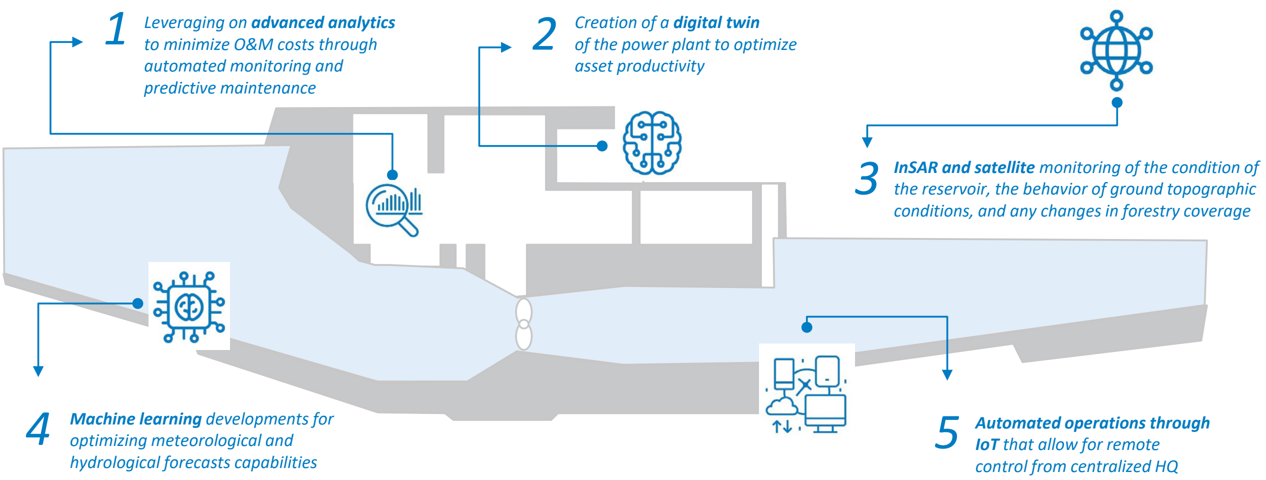
   Moreover, given that predictive capabilities and online monitoring will reduce the need for onsite inspections and other maintenance activities, the health and safety indicators of plant operators will improve significantly. Furthermore, stronger predictive capacity machine failure will reduce overall risks of hazardous events and decrease the risk of injury or death-related incidents.

   Observed KPI improvements:

   - Up to 90% reduction in corrective maintenance costs.
   - Up to 50% in mean time to failure of critical equipment.
   - Up to 30% reduction in inventory costs of maintenance spare parts.
   - Up to 2% increase in plant availability.

2. **Digital twin solution for next-generation hydro asset management.** A digital twin – the virtual simulation of a plant's physical processes through the integration of billions of 3D coordinates – archives photograph collections, construction blueprints, and historic data points of operational performance and allows operators to simulate, track, and optimize multiple operational and business variables of the hydro operational model and the functioning of critical assets. A digital twin hydro application can maximize plant productivity by optimizing energy dispatch,

Figure 4: High-impact digital solutions for hydropower operations



Source: Arthur D. Little analysis

increasing efficiency of maintenance interventions, and adjusting with great accuracy the life trajectories of the asset. A digital twin further allows stress-testing of the hydro assets under several operational and business scenarios that strengthen the risk management process of the plant operation.

Observed KPI improvements:

- Up to 10% reduction in overall maintenance costs.
- Minimized plant outages and corrective maintenance costs.
- Reduction of up to 50% startup time.
- Up to 2% increase in plant dispatch performance (given a constrained optimization plant production setting).
- Increase in the economic dispatch of the plant and increase in plant lifetime.

3. **InSAR technologies for topographic monitoring and stronger ecosystem overwatch.** InSAR (Interferometric Synthetic Aperture Radar) technology allows for high-density measurements over large areas of terrain identifying millimetric movements on the earth's surface. Such possibility provides valuable data for hydropower operators to monitor changes in the topographic condition of the ground, which will help in spotting any critical geological phenomena that can compromise dam infrastructure. This is especially critical for dams located in unstable geological settings. Moreover, such precision in ground observations can also monitor with high accuracy any changes in the vegetation coverage of surrounding terrain, strengthening the operator's capabilities of ecosystem overwatch.

Observed KPI improvements:

- Decreased costs of terrain overwatch.
- Decreased costs of corrective maintenance of roads or facility damage by geological instability.
- Strengthening of ecosystem overwatch.

4. **Machine learning to enhance forecasts capabilities and achieve higher commercial optimization.** Recent development in meteorological data provision systems that provide reliable intra-hour information can feed short- and medium-term hydrological forecasting models. Enriching such models with data of higher quality enables ML algorithms to generate forecasting outputs with minimized deviations. In return, a higher predictability of the water supply can seize better market opportunities to maximize revenue.

Observed KPI improvements:

- Up to 10% improved accuracy in mean absolute percentage error in short-term meteorological and hydrological forecast.
- Up to 1% improvement in operational revenue.

5. **Automated monitoring through Internet of Things (IoT) for seamless remote operation.** The increase capacity of network communications and the ubiquitous deployment of sensors on critical hydro equipment has permitted the remote centralization of plant operations through an integrated SCADA system. Unlocking remote plant control under a centralized unit has allowed world-class hydropower operators to minimize onsite personnel, increase operational performance of their plant portfolio, and improve the decision-making process of management.

Observed KPI improvements:

- Optimization of onsite plant personnel by up to 40%.
- Increased data-generation capacity up to 1,000x data points versus periodical or onsite inspection measurement.
- Increased labor productivity by up to 80%.
- Improved plant reliability and support cost-optimization efforts.

Project case – Digital transformation of a hydropower generator

We helped a leading hydropower operator in the Americas with an installed capacity of almost 3,000 MW to envision, design, and execute a cost-optimization strategy that leverages heavily on digital operations solutions.

After identifying critical cost areas and major efficiency gaps, we prioritized key operational initiatives and digital solutions that could achieve at least a 15%-20% reduction of OPEX within a five-year implementation time frame, which included key high-impact, low-hanging fruit initiatives achievable in a one-year horizon as well as more capital-intensive, high-return initiatives that required a longer time frame to attain the expected ROI.

Among the digital solutions conceived for our client's digital transformation, we evaluated advanced analytics to enhance predictive maintenance capabilities, satellite technologies embedded with AI to improve meteorological forecasts, drones and other unmanned vehicles for dam inspection and forestry oversight, radar technologies for topographic monitoring of road infrastructure, and even smart glasses to facilitate remote and efficient maintenance activities.

We developed a clear implementation roadmap to enable the client to fulfill a cost-optimization target, achieve significant operational efficiencies, and accelerate digital transformation. A successful implementation will require the company to guide the cost-optimization process in parallel with: (1) change management strategy that aligns the process with the organizational culture; (2) clear communication and side-by-side alignment between IT and the Energy Production division; and (3) development of partnerships with technology suppliers.

4. Digital maturity of the hydropower operational model

Prior to implementing solutions, it is of paramount importance to first understand the positioning of the hydropower operator in terms of digital maturity within the hydropower operational value chain. Identifying key digital gaps is essential to building a sustainable and effective digital operational strategy. We have developed a digital maturity model for hydro operators that can provide a baseline for management in order to envision, plan, and execute its digital strategy (see Figure 5). The maturity model covers four key stages that evolve from a conventional model, where most operations are manually intensive and asset management centers on reacting to critical equipment failure, to a final stage, where a fully automated operation is achieved and asset management reaches a holistic focus that integrates operational, financial, and risk management levers to business outcomes.

Stage 1: Conventional plant operations

At this stage, there is little awareness at an organizational level regarding the need to implement digital solutions. At an operational level, most activities occur onsite by personnel with no process or equipment automation. Maintenance is mostly preventive, meaning equipment intervention follows strongly with OEM recommended guidelines. This increases the probability that assets will be over-maintained, which translates to increased costs and no certainty that corrective failures will be fully avoided. Most inspections of critical equipment are carried onsite, and the data collection process is gathered for functional reporting only, rather than for generating valuable insights for management. Moreover, data, if even properly collected, will be scattered around different silos, making analysis even more difficult.

Figure 5: Digital operational maturity model for hydropower plants

Digital operational maturity →

Value chain levers	1 *Conventional plant operations*	2 *Digitally aware plant operations*	3 *Digitally smart plant operations*	4 *AI-driven autonomous plant operations*
Operations ***Key questions:*** *1. What is the capacity for remote operation?* *2. What is the level of automation?*	■ **Onsite operations**, with dedicated personnel in each plant ■ Entirely manual activities for machine operations	■ **Limited remote operations** from centralized unit, but prevalence of some onsite personnel ■ Some exploratory automated activities	■ **Fully centralized and remote operations**, with satellite personnel for specific onsite activities ■ Early implementation of automatization of operational activities	■ **Fully remote, automated, and autonomous operations** across all processes, including plant operations, surveillance, appraisal, and maintenance ■ Minimized human intervention
Maintenance ***Key questions:*** *1. What kind of maintenance scheme prevails?* *2. How does the operator monitor critical equipment?*	■ **Preventive maintenance,** guided time-based interventions based on OEM guidelines ■ High intensity of onsite monitoring activities	■ **Condition-based maintenance,** guided by the condition of the machine, obtained from periodic measurement of state and process variables intervention decision ■ Some onsite inspections carried out for data collection	■ **Predictive maintenance,** guided by the probability of occurrence of equipment failure ■ Onsite inspections minimized	■ **Autonomous maintenance,** guided by decision of ML and AI protocols on equipment failure prediction ■ Onsite interventions only necessary for maintenance
Asset management ***Key questions:*** *1. What is the focus on asset productivity?* *2. How is data managed for asset performance?*	■ **Reactive focus,** centered on asset reliability only ■ Limited operational data scattered through silos and utilized only for functional objectives	■ **Operational focus,** centered on asset reliability and cost performance ■ Increased operational data from more measurement points; data integrated into a single and opened source	■ **Integrated focus,** centered on asset reliability, cost performance, and lifetime maximization ■ Expanded operational data though increased connected devices, utilized to maximize asset lifetime	■ **Holistic focus,** centered on asset productivity and risk management ■ Operational data continuously gathered and modeled, utilized to feed ML protocols and for risk management
Digital enablers	*ERP* *Centralized servers or cloud/edge solutions*	*Data integrator (IPaaS)* *EAM*	*Big data + advanced analytics* *IoT + smart devices*	*ML + AI* *Digital twin*

Source: Arthur D. Little analysis

The asset management mindset centers around plant reliability, since the main concern is to prevent any corrective failure of critical equipment; cost efficiency, maximizing the asset lifetime, or risk management concerns are out of scope.

Key digital enablers – implementing an **enterprise resource planning (ERP)** solution and standardizing and **centralizing server infrastructure** will allow the hydropower operator to organize and standardize operational processes and at least provide a reliable data storage mechanism.

Stage 2: Digitally aware plant operations

In this second stage, the hydropower operator acknowledges the value of digital solutions to the hydro business model and has commenced an exploratory phase of testing new potential solutions to enhance productivity and maximize business value. At an operational level, some form of remote operations is being implemented from a centralized headquarter, but onsite personnel still remains in the plant. Maintenance planning and execution have transitioned from a purely preventive mindset to a more condition-based maintenance scheme, which decreases maintenance costs significantly as equipment intervention will depend on its condition; nevertheless, risk of failure remains given equipment is allowed to operate beyond the time frame recommended by the OEM. Through a condition-based maintenance approach, data collection becomes critical, and digital solutions should aim to continuously and increasingly collect multiple data points.

The asset management mindset will look toward reaching operational efficiency, where plant operators must achieve the highest levels of machine reliability while also minimizing operational costs.

Key digital enablers – implementing a **data integrator** solution becomes a key tool to standardize, and group data is now being collected from multiple measurement points as a result of a condition-based maintenance approach. Additionally, deploying an **enterprise asset management (EAM)** – or computerized maintenance management system – tool enables plant operators to have continuous oversight on the performance of the entire hydro asset portfolio.

Stage 3: Digitally smart plant operations

In the third stage, the hydropower operator is in the midst of an implementation phase of multiple digital solutions to enhance the hydropower operating model. At an operational level, the organization has achieved the ability to remotely control most hydropower plants from a centralized unit, only leaving satellite teams for specific maintenance execution activities. It leverages heavily on IoT sensors in critical hydro equipment and smart devices to facilitate automatized activities, collect data on a continuous basis, and strengthen the remote operation of the plants. Through such continuous collection of data, the operator can now conduct advanced analysis of its equipment's historic and actual performance to estimate with great accuracy the probability of the occurrence of equipment failure, which means that maintenance is now mostly of a predictive nature.

Besides the operational performance of assets, the asset management mindset additionally focuses on extending the lifetime of the equipment, minimizing CAPEX investments, and strengthening the organization's balance sheet.

Key digital enablers – implementing a **big data and advanced analytics** solution allows the organization to process, model, and structure different levels of analysis to enrich business insights that will strengthen overall operational strategy. In addition, deploying **IoT and smart devices** on a wide scale will enable a fully loaded remote operation that will optimize personnel, minimize operational risks, and enhance plant productivity and performance.

Stage 4: AI-driven autonomous plant operations

The hydropower operator has managed to reach a digital mindset of continuous improvement and self-actualization of its technological frontier. At an operational level, a fully automated and remote model guides performance in all plants with minimum involvement of personnel, which now is mostly dedicated to analytical improvement rather than functional compliance. Maintenance is not only predictive, but autonomous, where ML solutions enable the development of artificial neural networks, which predict the probability of failure or tear and also identify the corrective course of action to take. All data processing and storage goes through seamless processes, which model and calibrate operational and maintenance protocols, achieving the highest operational efficiency.

The asset management mindset is holistic in focus, where asset performance aligns with the organizational business and strategic objectives and is capable of strengthening the risk management capabilities of the plant operators. Additionally, operational decisions take into account the changing market environment through optimized commercial decisions on energy dispatch and also is keenly aware of the importance of climate change on operational outcomes, having strengthened its forecasting tools to increase the preventive capacity of water supply fluctuations.

Key digital enablers – developing **ML and AI capabilities** for the processing and modeling of data that feeds a **digital twin** of critical assets and unblocks the full potential of an autonomous plant, which drives and creates business value for the hydro operator.

Industry case – The strategic road to predictive maintenance of Enel Green Power

Enel Green Power, the dedicated business unit of the global multi-utility company Enel, manages an enormous holding of renewable energy–generation companies that have almost 50 GW of installed capacity, of which over 28 GW are in hydropower generation distributed in almost 800 power plants in 15 different countries. Within its vision of becoming a digital energy platform, Enel Green Power sees advanced analytics as a cornerstone of its digital transformation in energy generation. The operator is implementing an unprecedented rollout of a predictive analytics overhaul in almost 300 of its hydropower fleet, which represents nearly 17 GW of installed capacity. Its strategy under the name of "PresAGHO" (Predictive System and Analytics for Global Hydro Operation) aims to fully transition its maintenance scheme form a purely preventive, or condition-based, model to a fully predictive maintenance one by the end of 2022.

Transitioning to predictive maintenance will require the massive deployment of sensory equipment to be installed in almost all critical and peripheral equipment of the hydropower plant, in addition to integrating new data points to a centralized unit and preparing the needed digital capabilities within the organization. This would allow Enel Green Power to successfully make use of the information and develop the required algorithms that will allow it to fully strengthen its capacity to model and detect machine failure.

The implementation strategy will vary based on the requirements and characteristics of each plant. Enel Green Power is pursuing a differentiated approach between large, medium, and small plants; identifying synergies with existing operational equipment; and identifying the right digital platform to support a predictive maintenance model.

To assure a successful implementation, Enel Green Power is partnering with key major OEMs and digital solutions providers to implement pilot tests of different analytics and sensorics solutions and eventually build up scale to cover its intended target of 300 hydropower plants.

The new maintenance schemes will improve planning, optimize costs, reduce person-hours and improve the overall quality of monitoring and control – setting the company at the forefront of digital transformation of hydropower operations.

5. Key success factors for hydropower digital transformation

For hydropower operators to achieve a successful digital transformation, they must consider the following four key success factors, which will allow them to set the direction of the digital maturity process and maximize value from the deployment of digital operations solutions.

1. Well-defined digital strategy and ambition

There is no one-size-fits-all digital strategy for hydro operators. Management must identify its operational efficiency gaps, its medium- and long-term business strategy, and its budget constraints – before thinking of bootstrapping its digital transformation.

Those efficiency gaps need to consider recurring operational problems that are driving O&M costs; the decision to automate processes or implement digital solutions should be tailor-made to those critical operational lags. The business strategy must have clear objectives regarding operational efficiency goals and defined growth drivers, including potential new business models in the energy value chain that will need a digital platform to scale. Budget constraints, given in the form of investment priorities for growth or even shareholders' objectives, must be considered in order to align the potential digital dividend with the company's return expectations.

Identifying and prioritizing critical areas within the hydro operational model will set the direction and ambition of what digital solutions to implement as well as the pace of digital maturity that the company is able and willing to pursue.

2. Change management, agile mindset, and digital culture

The process of digital deployment typically will be resisted within an organization that sees all digital as a threat to the status quo. Within hydropower operators, this is especially critical for those with an aging workforce or if they are or have been a state-owned company; both favor the comfort and stability of conventional operational models. Offering training of digital capabilities; developing a digital culture; communicating the digital ambition, purpose, and value for each solution; and describing the overall benefit that will be acquired by employees is critical to reach a seamless digital evolution.

Digital operations solutions are rapidly evolving and increasing in possibilities of application. The digital hydro organization must be able to identify and prioritize suitable digital solutions to its operational needs and, most important, must be able to pilot and, if needed, fail rapidly. During this process, generating alliances with digital solutions vendors will be key, as this will allow for the minimization of costs in pilot testing while also generating a symbiotic buildup of operational and technological knowledge, which will be key to a successful solution-scaling phase.

This is a tremendous challenge for hydro operators, as their technological frontier has been rather unchanged in the last decade. Breaking technological attachment and being able to innovate, applying Agile methodologies in planning and execution based on MVPs (minimum viable products), and implementing at an efficient and effective scale will be key to move ahead along the digital maturity curve.

3. Robust data governance

The key resource within a digital maturity process is the overall management of operational data. Integration, interoperability, standardization, and open access must govern the generation, gathering, collection, storage, and processing of data across the entire organization. Thus, establishing a solid data governance framework from the start will allow hydro operators to scale seamlessly along the digital maturity curve.

4. Reliable and scalable cybersecurity capabilities

As the hydropower operator gains digital traction, deploying and implementing multiple data solutions will increase the level of connectedness and interdependence between critical hydro assets. The risk of compromising digital integrity by a cyberattack therefore is elevated. A fully autonomous hydro plant should have robust cybersecurity defense protocols against data vulnerability, plant shutdowns, or even a plant ransomware attack.

Conclusion

The hydropower business urgently needs to adapt to the new reality that's being shaped by the ongoing global energy transition. As greater uncertainty looms over rapidly changing energy markets, the digital race for asset productivity in hydropower generation is more evident than ever. The digital reckoning for hydropower has come – adaption can only be achieved through a strong and dynamic digital shift strategy. Integrating a digital ambition with clearly defined business objectives and pushing forward on an organizational commitment to promote operational change will be key change levers that will allow hydropower operators to reap the benefits from the multiple digital operations solutions now applicable.

Now is the time for management to identify the operational efficiency gaps of their hydro operations; recognize their organizational limitations and level of digital maturity; and step up to disrupt old operational paradigms in order to embrace technological evolution.

Note: Although digital operations technologies offer a wide spectrum of applications across all functional areas and stages of the plant value chain lifecycle of the hydropower organization, this Report has focused exclusively on the operational nature of the hydropower business model. As such, it did not provide focus on the impact of digital technologies in core support functions, such as finance, human resources, trading, procurement, or others. Additionally, it excluded potential applications in other stages of the hydropower value chain, such as planning, building, refurbishments, or plant decommissioning processes.

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