Title: Energy/Water Operation Smart Contract for Hydropower Plant/Data Centers

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The team with collaboration of Tennessee Valley Authority (TVA) for providing the data of generator motor pump machines, substation switchyards, protective relay/ meter models, water reservoir level limits, power flow data, load peak demands, MW-h cost/ price, and other information.

Focal Area: This main topic focuses on the "energy/water operation and optimization of hydropower plants with data centers" to implement a secure, reliable, and decentralized operations/billing smart contract using Distributed Ledger Technologies (DLT) at the points where a hydropower plant connects with data centers (cluster). Distributed Ledger Technology (DLT) is a decentralized system where records of transactions are shared, synchronized, and validated across multiple nodes instead of relying on a single authority. It ensures transparency, security, and immutability by distributing identical copies of the ledger to all participants in real time. Data centers are critical customers for electrical utilities—especially hydropower plants—which can provide large amounts of energy. As the number of data centers continues to rise in the coming years, powering their infrastructure—such as heating, ventilation, and air conditioning (HVAC) systems, as well as IT equipment like servers, uninterruptible power supplies, and other devices—remains crucial for government missions that aim to integrate reliable energy (from hydropower plants) with data centers for the advancement of artificial intelligence (AI).
Small- to medium-sized data centers typically consume between 1 and 10 MW of continuous power while large data centers may consume between 60 and 90 MW. Because hydropower plants produce energy consistently, they can power multiple data centers (clusters) and meet the high energy demands of companies like Google and Digital Realty through long-term agreements with major energy providers. This supports the growing energy needs of data centers during their energy-intensive operations. In this context, we propose an operations/billing smart contract application using DLT. This application will set the megawatt-hour (MW-h) price for data centers by factoring in the integration of their backup diesel generators during peak load demands on the grid or during motor pump operations at hydropower plants. The result is a secure, reliable, and decentralized operations/billing smart contract platform that connects hydropower plants and data centers (clusters).

Existing Challenge- integration of data centers and hydropower plant operation: The increasing number of data centers driven by AI applications will require large amounts of reliable and consistent electrical energy. Hydropower plants normally respond fast in response to varying power demand and can therefore offer an excellent source for supplying energy to these data center clusters. In addition, data centers typically rely on numerous diesel generators to provide energy during grid blackouts. However, infrequent use of these diesel generators can increase maintenance and operational costs. Furthermore, these diesel generators can supply energy back to the electrical grid, particularly during periods of peak demand or when hydropower plant motor pumps are needed to restore reservoir water levels. In this way,

hydropower plants could offer competitive megawatt-hour (MW-h) pricing to data center clusters based on mutual benefits. Both data centers (clusters) and hydropower plants can optimize energy consumption and generation—as well as reservoir water levels—by using an operations/billing smart contract. Data centers and hydropower plants connected to the electrical grid would benefit from a secure and reliable platform for customer-partner operations. Distributed Ledger Technologies (DLT) provide a promising alternative for implementing such smart contracts. Implementing DLT to establish a secure, reliable, and decentralized energy transaction operations/billing smart contract between data centers (clusters) and hydropower plants creates an economically advantageous opportunity. This proposal enhances the mutual benefits between hydropower plants and data centers through a virtuous energy-water cycle system (see Figure 1a). Because data centers require energy for HVAC systems and IT equipment, a mutually beneficial energy-water cycle supports the use of smart contracts via DLT. This implementation, named the "Energy/Water Operation Smart Contract for Hydropower Plants/Data Centers", leverages DLT's inherent attributes of reliability, security, transparency, and decentralized control. Figure 1a illustrates the energy-water cycle system between data center clusters and hydropower plants. Under normal conditions, the hydropower plant supplies energy to both the data centers and the rest of the grid (Figure 1a:1-2). In the event of a blackout, data centers rely on their diesel generators (Figure 1a:4-3). Additionally, during typical grid operation, these diesel generators can contribute extra energy when hydropower plants operate motor pumps to restore reservoir water levels or during peak load demands (Figure 1a:4-5). Based on this concept, data centers (clusters) and hydropower plants can employ an energy operations/billing smart contract using DLT. Under this arrangement, the MW-h price for data centers will be set by incorporating their backup diesel generators into the electrical grid. Figure 1b illustrates a hydropower plant with data centers (clusters) using diesel generators.

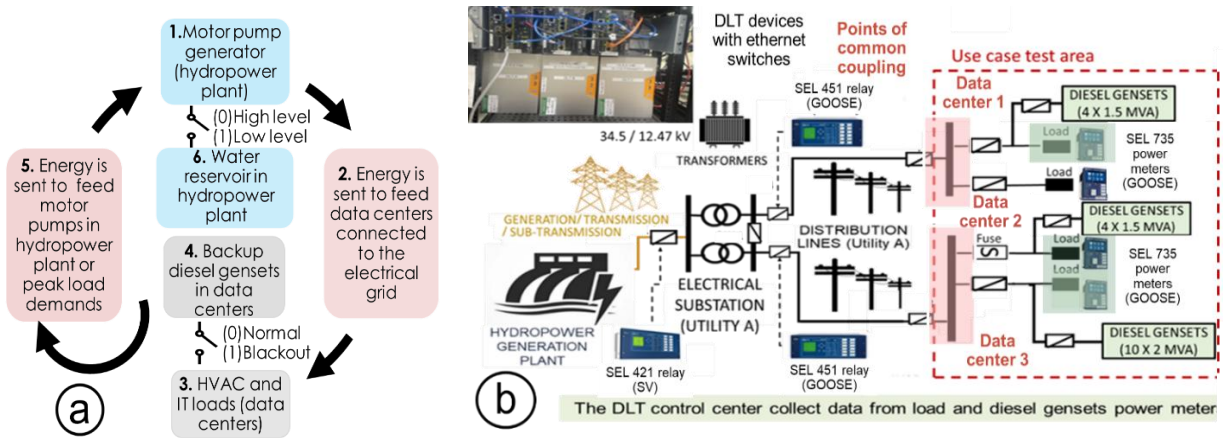


Figure 1: Energy/water mutual benefit circle (a) and hydropower plant with data centers (b)

Near-Term Opportunity: The main opportunity lies in integrating the mutual benefits between hydropower plants and data center clusters through a virtuous energy-water cycle system. Since data centers require energy for HVAC and IT equipment, a mutually beneficial energy-water cycle between data center clusters and hydropower plants supports the use of DLT and smart contracts to implement the "Energy/Water Operation Smart Contract for Hydropower Plants/Data Centers" using a secure, reliable, transparent, and decentralized DLT system. The electrical substation grid (ESG) testbed—comprising more than twelve relays/meters in the loop and real-time simulators—will be utilized. This ESG testbed is in the Advanced Protection Lab

at the Grid Research Innovation Development Center (GRID-C) at Oak Ridge National Laboratory. It can create realistic power system test scenarios that electrical utilities are unlikely to perform in the field due to the risk of equipment damage and blackouts; these include temporary or permanent electrical faults, breaker miss operations, and cyber-attack scenarios. The Advanced Protection Lab environment is ideal for safe and repeatable experimentation using the ESG testbed, which consists of:

- A protection and control system that optimizes and manages the breaker operations of the electrical grid configuration with the hydropower plant connected to the data centers, enabling the tripping/closing of breakers during normal operations and electrical faults. Digital twin for hydropower system developed at ORNL will be used to simulate and validate the protection and control system.
- A measurement and communication system that collects data—including phase voltage/current magnitudes and angles, electrical power, power factor, frequency, and breaker states—from the protective relays/meters at the hydropower plant substation and the data centers' point of common coupling in the electrical grid.
- A synchronized time system that utilizes the Inter Range Instrumentation Group (IRIG)-B and precision time protocol for protective relays, meters, and DLT devices with their Ethernet switches.
- A cyber grid guard system featuring three CISCO Ethernet switches and DLT devices to hash data from the protective relays/meters of the data centers and hydropower plant, ensuring data integrity and security for the energy/water operation smart contract.

The partnership with the Tennessee Valley Authority (TVA) will provide critical data regarding generator motor pump machines, substation switchyard configurations, models of protective relays/meters, water reservoir level limits, power flow data, load peak demand, MW-h costs/prices, and other information. This data will enable us to create accurate models for the electrical grid in the real-time simulator and integrate these models with protection and control, measurement and communication, synchronized time, and cyber grid guard systems. The hydropower plant model is based on a MATLAB/Simulink hydraulic turbine and governor model, which will be upgraded using data from the Raccoon Mountain hydropower pumped storage plant.

Success Measure: The "Energy/Water Operation Smart Contract for Hydropower Plants/Data Centers" is based on a hardware-in-the-loop platform that uses a real-time simulator connected to protective relays, power meters, and DLT devices. This platform is used to develop the metrics, implementation standards, and evaluation framework necessary for prioritizing and assessing smart contracts in real scenarios between hydropower plants and data center clusters. The "Energy/Water Operation Smart Contract for Hydropower Plants/Data Centers" will be implemented using a measurement and communication system that incorporates protective relays and/or meters located at the common coupling points between the data centers and the electrical grid, as well as at the hydropower plant substation (see Figure 1b). Data on phase currents, voltages, and breaker states under normal operation, during peak load demand, and in blackout scenarios will be collected to inform the algorithms used in the smart contracts. The DLT devices will gather and hash this data from the protective relays and power meters, enabling the optimization of the energy/water operation between the data centers and the hydropower plant.

At the hydropower plant, the pumped-storage unit can operate either as a motor or as a generator. Consequently, the smart contract will focus on optimizing the operation of the generator/motor pumps (hydropower plant), backup diesel generators (data centers), peak load demand on the electrical grid, and reservoir water levels (dam) by implementing an energy-water cycle system (see Figure 1a) between the data centers and the motor pumps at the hydropower plant. The measured power flow between the data centers and the hydropower plant will inform decisions—such as the availability of backup diesel generators to cover peak grid demand or feed energy to the hydropower plant's motor pumps to raise reservoir water levels. Moreover, a variable energy operations/billing system will be implemented using DLT, with the MW-h price for data centers determined by integrating their backup diesel generators into the electrical grid.

Dr. Emilio Piesciorovsky is the Testbed Development & Advanced Protective Relaying expert at ORNL with 20+ years of expertise in electric-grid protection, DER integration, and hardware-in-the-loop (HIL) testbeds. Leads end-to-end substation testbed development and validation to ensure robust protection and fault-tolerance.

Raymond Borges Hink — Principal Investigator and Project Lead at ORNL. 15+ years of expertise in cybersecurity for electric grids, cyber forensics, distributed ledger technology (DLT), and grid resilience. Leads DOE-funded efforts spanning advanced protection systems, intrusion detection with machine learning, and grid communications; experienced in designing scalable, interoperable systems and directing multi-directorate and multi-institution teams.

Dr. Aaron Werth is a Cybersecurity Research Specialist at ORNL. Expertise in cyber-physical systems, control systems, and critical-infrastructure cybersecurity. Background includes SCADA testbeds, DLT, and control-system security; recent work on modular SCADA virtualization and co-authored publications applying DLT to fault detection and grid monitoring.

Gary Hahn is the DLT Development Lead at ORNL. Expertise in hypervisor technology, secure code development, and DLT frameworks for high-performance grid systems. Contributions include modular software architectures and cross-platform implementation of DLT components to support resilient grid operations.

Dr Hong Wang is a Fellow of IEEE and has been working on hydropower system modeling and control for 30+ years. He is the PI for Digital Twin for Hydropower Systems projected funded by WPTO and has published 300+ technical papers and 6 books in advanced control system research.

Dr. Ali Riza Ekti is a Senior R&D Staff Member the Group Leader of the Grid Communications and Security Research Group in the Electrification and Energy Infrastructures Division at Oak Ridge National Laboratory (ORNL). He holds a Ph.D. in electrical engineering from Texas A&M University and has held academic and industry leadership roles including as Associate Professor at the University of Tennessee–Bredesen Center since December 2022. His research focuses on statistical signal processing, anomaly detection and classification in smart grids, wireless sensor networks, machine-learning applications in grid communications, and propagation-channel modeling for 5G and beyond systems.