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Hydropower Resilience Database for Assessing Microgrid Formation Capability and Enhancing Power Grid Resilience

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SUMMARY

In the face of increasing frequency of extreme events, enhancing resilience and reliability of energy infrastructure demands innovative solutions. Hydropower, with its inherent generation flexibility and grid-forming capability, offers significant potential for enhancing power grid resilience through the establishment of microgrids. To enable informed decision-making and strategic planning, we present the Hydropower Resilience Database (HRD) that integrates data from various sources such as Oakridge National Laboratory (ORNL) HydroSource, National Inventory of Dams, and US Western Grid database. By integrating relevant information on hydropower plant characteristics, including dams, reservoirs, and connected electrical grid, this resource enables hydropower plant owners, utilities, and community stakeholders to identify and evaluate the feasibility of using hydropower resources in microgrids to support nearby communities and critical infrastructure in various challenging scenarios. Using HRD, a set of metrics are evaluated to quantify the capability of hydropower plants to support essential microgrid functions. An interactive tool is developed using ArcGIS, enabling the visualization and analysis using HRD. Our research contributes to strategic planning efforts for fortifying energy infrastructure, ensuring reliable power supply during disruptions, and advancing the development of robust and resilient energy systems in regions susceptible to grid vulnerabilities.

KEYWORDS

Hydropower resilience database, microgrid formation, grid resilience, combined data integration.

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1. Introduction

In recent years, modern power systems have encountered significant challenges in maintaining reliable electricity access and availability in the face of extreme weather events and other high-impact low-probability disruptions. These events can have severe consequences, leading to widespread power interruptions and incurring substantial costs. For instance, the devastating Winter Storm Uri in Texas, United States, in February 2021 caused widespread power interruptions that left 4.5 million customers without power supply [1]. Additionally, during the year 2022 alone, there were 18 weather-related disasters in the United States, each costing more than $1 billion [2]. These incidents underscore the urgent need for resilient planning strategies that can enhance the grid's ability to withstand and recover from such events.

In response to these challenges, there is a pressing need to explore innovative approaches to enhance the resilience and reliability of energy infrastructure in vulnerable regions. Distributed energy resources (DER) and microgrids have emerged as potential solutions for withstanding and recovering from the catastrophic effects of weather-related extreme events like wildfires [3]. Microgrids, which can operate independently or semi-independently by islanding off from the larger grid, offer localized energy systems that can maintain essential services during grid disruptions caused by disasters [4]. These microgrids can be deployed at various scales, encompassing individual buildings, campuses, neighborhoods, or even entire communities, providing an effective means of enhancing local resilience [5].

In regions like California, where wildfires have interacted with power transmission systems, utilities have resorted to proactive measures, such as public safety power shutoffs (PSPS), to prevent wildfires ignited by power lines [3]. However, while PSPS events are essential for safety, they can leave communities without electricity for extended periods, emphasizing the need for reliable local backup generation solutions [6]. Subsidized generators and distributed batteries have been considered as potential remedies, but they come with environmental and logistical challenges, including air pollution, noise, and fuel transportation issues [7]. In this context, hydropower plants have emerged as a promising solution for enhancing resilience and supporting communities during PSPS events. Unlike intermittent renewable sources like wind and solar, hydropower offers a dispatchable and flexible energy resource that can rapidly adjust its power output to meet changing electric demand. Hydropower plants can provide spinning and operating reserves, offer primary frequency response, and contribute to voltage support during unexpected contingencies. Furthermore, hydropower plants require low station power and can serve as black start resources for grid restoration.

While hydropower plants offer significant benefits during extreme grid events, their effectiveness can be influenced by drought conditions and hydrological factors [8]. Understanding the capabilities and limitations of hydropower plants is essential for evaluating their suitability in forming resilient microgrids. Therefore, this research paper presents the development of the Hydropower Resilience Database (HRD), leveraging data from reputable sources, to assess the microgrid formation capability of hydropower plants and their potential contributions in enhancing resilience. By characterizing hydropower plants based on their capabilities and limitations, this study aims to identify suitable candidates for microgrids to support communities during extreme grid outages. The findings of this research will contribute to informed decision-making and strategic planning efforts aimed at strengthening energy infrastructure and enhancing resilience in vulnerable regions.

The rest of the paper is organized as follows. Section 2 presents a review of various hydropower databases. Section 3 discusses the significance of the hydropower resilience database. Section

4 discusses the development of HRD and its visualization using ArcGIS platform. Section 5 discusses the hydropower characterization metrics and presents an evaluation these metrics for a set of hydropower plants. Finally, Section 6 provides the conclusion and future work.

2. Existing Hydropower Database

In this section, we provide a review of the existing hydropower databases utilized in this research, namely the Oakridge National Laboratory (ORNL) hydropower database, National Inventory of Dams (NID) database, and the US Power Grid database. Each of these databases offers unique insights into hydropower plants, dam structures, and electrical system parameters. We highlight the advantages and limitations of each database, focusing on their relevance to the assessment of microgrid formation capability and grid resilience.

2.1. ORNL HydroSource

The ORNL HydroSource database serves as a crucial National Water-Energy digital platform for U.S. hydropower stakeholders [9]. HydroSource contains detailed information on over 2,300 hydropower projects across the United States. HydroSource provides extensive data on various hydropower projects, offering insights into crucial aspects such as project location, capacity, and operational status [9]. This information enables us to assess the availability of hydropower resources that could play a role in forming microgrids and supporting energy infrastructure during extreme events. The ability to gain valuable insights into the hydropower market, deployment, and resources assessment supports data-driven decision-making and contributes to the overall development of resilient energy systems. However, despite the wealth of information provided by HydroSource, it has limitations regarding dam information, generator electrical parameters, and comprehensive turbine and governor data. These parameters are vital for assessing the capability of hydropower facilities to support microgrid formation and contribute to energy resilience.

2.2. National Inventory of Dams (NID) Database

The NID is a congressionally authorized database that serves as a central information source for more than 91,000 dams across the U.S. and its territories [10]. Managed and published by the U.S. Army Corps of Engineers in cooperation with the Association of State Dam Safety Officials, states, territories, and federal agencies, the NID database contains over 70 data fields for each dam, offering comprehensive information about dam locations, size, purpose, type, last inspection, and regulatory details. The NID database plays a crucial role in understanding the relationship between dams and the areas they impact. It supports various users, including dam owners, operators, regulators, emergency managers, safety professionals, infrastructure owners, community leaders, business owners, and residents, in comprehending the implications of dam infrastructure on their surroundings. The NID serves as a valuable resource to enhance awareness of dams and prepare for dam-related emergencies, enabling users to access specific data about dams in the U.S.

The NID database is utilized in various ways, such as providing a centralized platform for dam owners, operators, and regulators to access and review data for dams under their jurisdiction. It assists political decision-makers, public safety officials, and flood risk managers in understanding potential flood risks associated with dam infrastructure. Furthermore, the information from the NID database is invaluable in the local development of emergency action plans, evacuation plans, and other emergency response activities, enabling officials to make informed decisions about emergency preparedness and response measures. Overall, the NID database provides crucial information about dam dimensions, regulatory facts, and flood inundation mapping for analyzing hydropower plants' suitability for microgrid formation. However, it is essential to acknowledge that the NID database, while providing valuable data on dam characteristics, does not encompass all necessary information about the hydroelectric plant and grid interconnection for microgrid feasibility analysis.

2.3. US Western Grid Stability Base Cases

The US Western grid stability base cases, facilitated by the Western Electricity Coordinating Council (WECC), plays a pivotal role in analyzing transient stability within electrical transmission networks [11]. This database in Power System Simulator for Engineering (PSS/E) comprises two main components: the load flow description ('.raw') and dynamic data ('.dyr') [12]. Leveraging PSS/E database is crucial in our efforts to develop electromagnetic transient models for hydropower generators and turbine-governors, enabling a comprehensive analysis of their behavior and performance under various operating conditions. The load flow description in the PSS/E database allows us to perform steady-state analyses of the power system transmission network. It provides essential information on voltage levels, power generation, and load demand, allowing us to understand the power system's operating conditions and identify potential challenges in maintaining stability during grid disruptions. By incorporating the load flow data into the hydropower database, we gain valuable insights into the interconnectedness of hydropower plants with the larger power grid, aiding in the assessment of their contribution to microgrid formation and grid resilience.

The dynamic data in the PSS/E database contains critical parameters related to hydropower generator models and turbine-governor models. It includes information on various generator and turbine-governor models, such as GENROU, CSVGN, IEEEG2, HYGOV, and more. By considering these dynamic parameters, we can simulate and analyze the response of hydropower generators and turbines to transient events, ensuring their stable operation under various system disturbances, including wildfires. In addition to the ORNL HydroSource and NID databases, the PSS/E database provides electrical, mechanical and control characteristics of hydropower plants, enabling evaluation of essential capabilities like reactive power, ramping, and dynamic response, which are critical for microgrid planning.

3. Significance of Hydropower Resilience Database

The significance of developing HRD lies at the core of this research paper. This section summarizes the rationale of combining data from reputable sources, including the ORNL HydroSource, NID database, and the US Western Grid Stability Base Cases for a more comprehensive HRD.

3.1. Enhanced Data Insights

The first and foremost significance of HRD is the enhanced insights it offers to researchers, planners, and stakeholders. The consolidation of data from diverse sources into a single repository offers a holistic view on hydropower plants' characteristics, capabilities, and limitations. Researchers gain access to valuable information about plant locations, storage capacities, operational parameters, and electrical system data, enabling a deeper understanding of hydropower resources' potential contributions to power system resilience.

3.2. Informed Decision-Making

A key advantage of HRD is its ability to inform decision making processes related to power grid resilience and energy infrastructure planning. By systematically screening and analyzing hydropower plant data, decision-makers can identify suitable candidates for powering energy infrastructures vulnerable to extreme weather events. This informed approach helps optimize resource allocation, investment, and strategic planning efforts, ensuring that hydropower facilities are utilized effectively to enhance the power grid's reliability and resilience during extreme events.

3.3. Microgrid Formation Assessment

With all relevant information on plant and connected grid infrastructure, researchers have access to parameters to model and simulate the performance of hydropower plants in microgrids under different operating scenarios. Researchers can narrow their focus to relevant hydropower facilities located in target regions (e.g., regions prone to wildfires). This targeted approach streamlines the analysis process, enabling a comprehensive evaluation of each plant's potential to form microgrids that can operate independently or in coordination with the main grid during extreme weather-induced disruptions.

3.4. Supporting Grid Resilience

With the insights provided by HRD, stakeholders can develop strategies to enhance resilience of power grid. Dispatchable and flexible hydropower resources offer rapid response capabilities, contributing to grid stability and providing crucial support during extreme weather events. Microgrids formed by hydropower plants can island off from the larger grid, allowing for localized shutdowns in an orderly manner, reducing the risk of grid-induced failures and ensuring the continuity of essential services in affected communities.

4. Hydropower Resilience Database and Visualization Tool

In this section, we present HRD along with its visualization tool, designed to enhance our understanding of hydropower plants' potential in forming resilient microgrids. We will delve into the steps involved in creating HRD and the visualization tool.

4.1. Hydropower Resilience Database Development

In this work, we are mainly focusing on four wildfire-prone states of the US: California, Oregon, Washington, and Idaho. We are analyzing 740 hydropower plants across these four states. Figure 1 shows the distribution of these hydropower plants in these four states in terms of size of the plant, number of units, and mode of operation based on ORNL HydroSource.

Figure 2 shows the steps involved in the development of HRD. The first step is screening data from HydroSource. We select hydropower plants based on specific criteria, including hydropower capacity between 1 MW and 200 MW, and the number of generating units required for the analysis (more than one). Additionally, we consider the plant type, whether it is run-of-the-river, peaking, or re-regulating to ensure that the selected hydropower plants align with our analysis goals. While we are not implying that any of the hydropower plants are unsuitable for a microgrid, we prioritize developing a comprehensive database with hydro plant candidates with the highest potential. The primary goal is to evaluate and test the utility of HRD using a selection of hydropower plant candidates. HRD will be progressively expanded in the future including remaining hydropower plants.

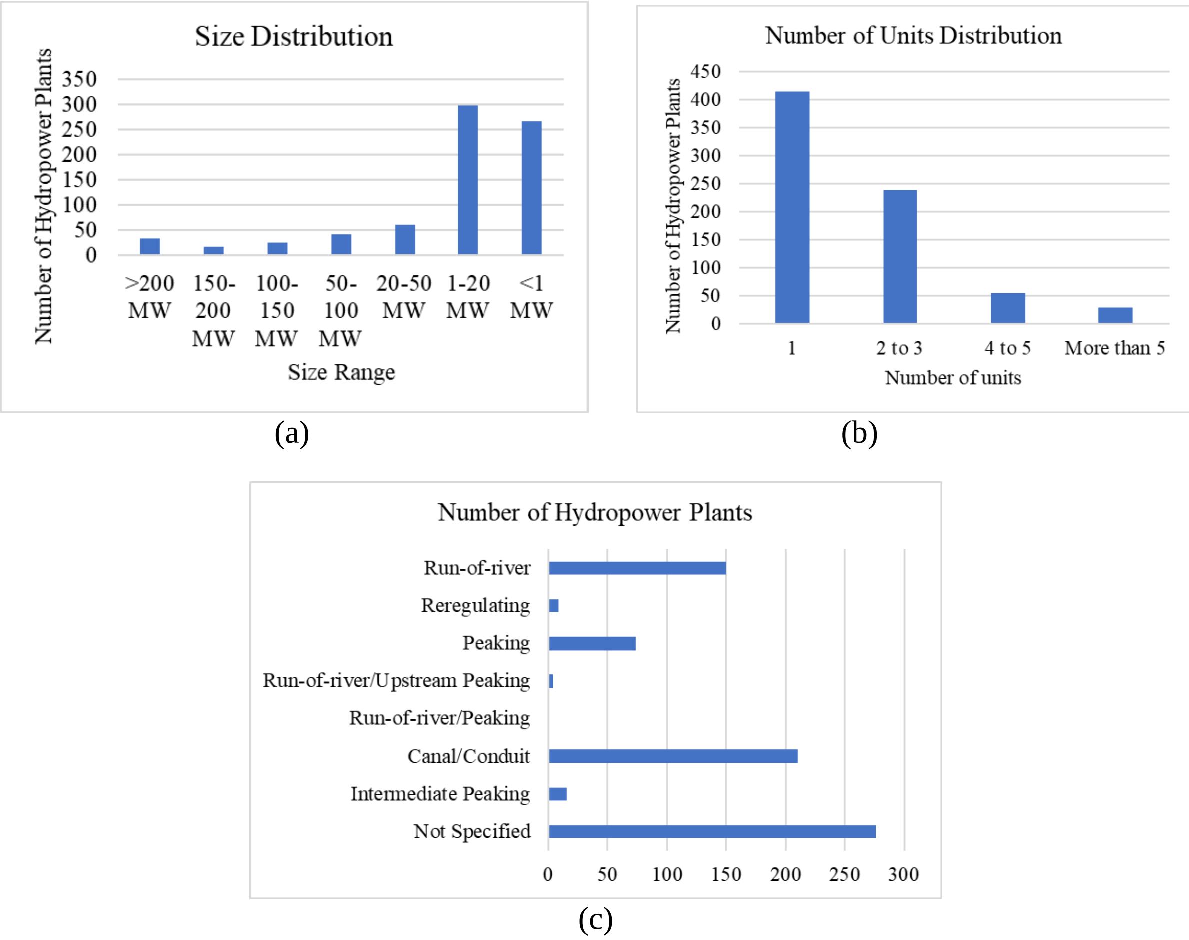

Figure 1 Distribution of various characteristics of hydropower plants in California, Oregon, Washington, and Idaho states for initial screening. (a) size of the plant, (b) number of units, and (c)mode of operation.

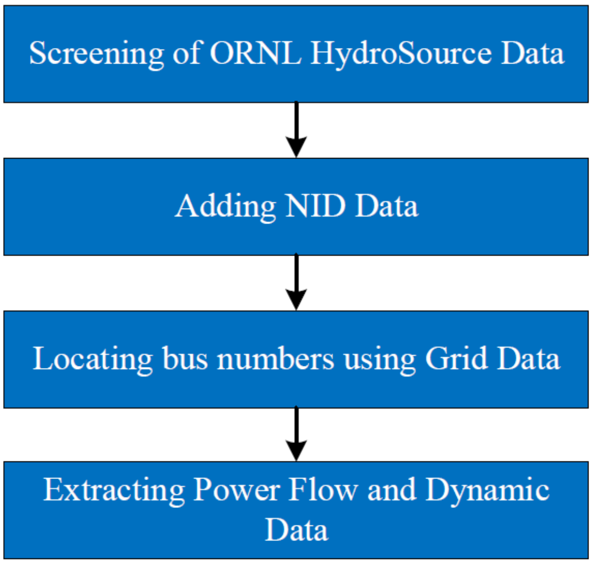

Figure 2: Steps for HRD Development

Next, we incorporate data from the NID into the screened hydropower dataset. By establishing a link between the ORNL HydroSource and NID using a common identifier, such as the NID ID, we enrich the database with essential information related to dam dimensions, including height, storage capacity, and relevant hydrological data.

The subsequent step involves locating bus numbers using the US Western Grid Stability Base Cases for each hydropower plant. As the ORNL HydroSource data does not include bus numbers, we manually search and find the exact names of each hydropower plant in the PSS/E database. This process enables us to identify the unique identifiers (bus numbers) for each hydropower plant, facilitating further integration with critical electrical system parameters. Once the bus numbers are determined, we add the extracted PSS/E power flow data, including information on Base kV, voltage limits, reactive power limits, and Base MVA, to HRD. This data provides crucial insights into the electrical characteristics of hydropower plants, supporting in-depth analysis of their capabilities in the context of microgrid formation. In addition to the static data, we extract relevant dynamic data from the PSS/E dynamic data file (.dyr), including parameters related to hydropower generator and turbine-governor models. This dynamic data enables us to simulate and analyze the behavior of hydropower plants under transient conditions, contributing to a comprehensive understanding of their performance during grid disturbances.

4.2. Database Visualization using ArcGIS Interactive Map

HRD, enriched with data from various reliable sources, was further utilized to create an interactive visualization using the ArcGIS platform [13]. This visualization aims to provide users with an intuitive and informative representation of different hydropower plants and their associated parameters, resulting in a better understanding of their potential for microgrid formation and energy resilience.

Figure 3 shows an interactive map created using the ArcGIS platform. In this visualization, each hydropower plant is represented as a distinct dot on the map, and users can navigate through the database by moving the cursor over these dots. When hovering over a specific dot, a pop-up window appears, displaying detailed information and key parameters for the corresponding hydropower plant. The information includes hydropower plant name, location, hydropower capacity, plant type, number of generating units, dam storage capacity, bus number, Base kV and voltage limits, reactive power limits, Base MVA, etc.
The interactive nature of the visualization allows users to explore the database dynamically, gaining insights into the key attributes and capabilities of each hydropower plant. By simply hovering over different dots on the map, stakeholders, including hydropower plant owners, utilities, communities, and microgrid planners, can quickly assess the suitability of specific hydropower resources for forming resilient microgrids.

Moreover, the integration of HRD into the ArcGIS platform offers additional functionality and possibilities for further analysis. Users can apply filters and query the database to identify clusters of hydropower plants with desirable attributes, such as high capacity and storage capability, ideal for microgrid development. This spatial analysis provides valuable inputs for decision-making processes and strategic planning in enhancing energy resilience through microgrid deployment.

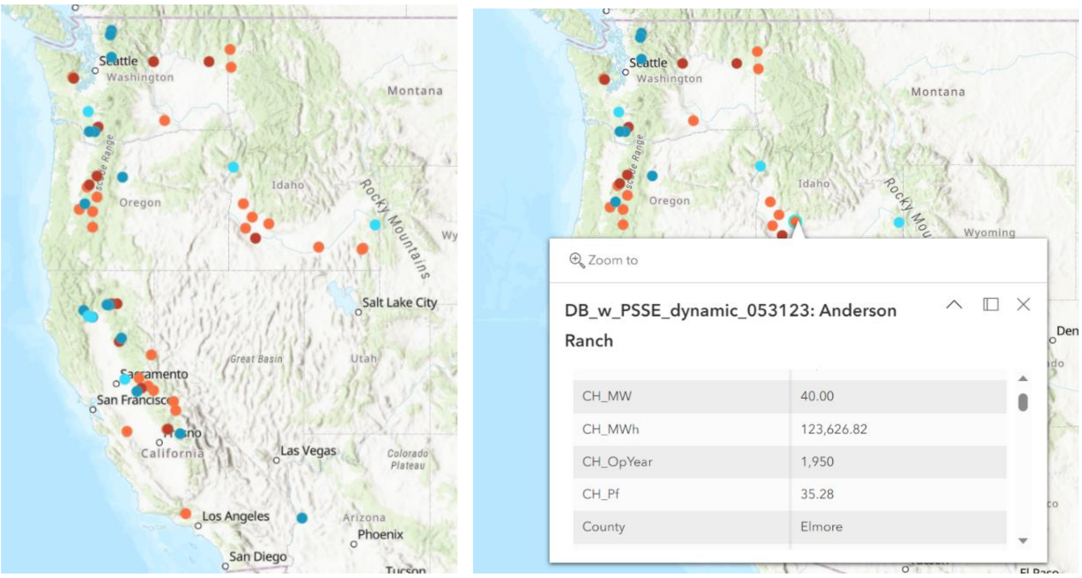

Figure 3: Interactive Map of Hydropower Plants using ArcGIS Platform

5. Hydropower Characterization Metrics

Utilizing HRD, we can evaluate and compare hydropower plants in terms of their capability for microgrid operation. Five key capability metrics are considered to assess the suitability of hydropower plants for forming and operating in resilient microgrids [14]. These metrics are as summarized in Table 1 with short description.

Table 1 : Capability Metrics Considered for Hydropower Plant Characterization

Metrics	Description
Microgrid Formation	This metric serves as the initial qualitative screening process, considering technical and regulatory constraints, to identify hydropower plants potentially suitable for microgrid operation. It accounts for factors such as plant size, type, and contractual obligations with transmission owners and utilities. Additionally, it considers the ability to curtail operations for meeting the resilience requirements of local loads during potential grid outages.
Reactive Power	Reactive power capability is vital for maintaining microgrid voltage at a standard level and efficiently distributing active power to end-users. This metric primarily depends on the generator's excitation system. Hydropower plants typically have high reactive power capability and are valuable for maintaining voltage stability.
Inertial Response	Inertial capability plays a critical role in arresting frequency excursions and maintaining dynamic stability during microgrid operation. It is essential during islanded operation when resources for providing inertial response are limited.
Ramping Capability	Ramping capability is the ability of hydropower plants to undergo operational ramps to adapt to new load conditions. Ramping is essential to avoid large frequency excursions and maintain stability during power output changes.
Storage Capacity	Hydropower's storage capacity is pivotal in providing continuous power supply to microgrid loads during long outages. It determines the ability of hydropower facilities to store and efficiently use energy to meet critical loads.

Figure 4 presents a spider chart with scores and comparisons among four hydropower plants located in Idaho in terms of the metrics discussed above. All these hydropower plants are sized between 1 and 100 MW, have multiple units, and offer peaking and regulating capabilities, making them suitable for microgrids. The Anderson Ranch and Black Canyon hydro plants are federally owned and operated by the U.S. Bureau of Reclamation, whereas the Swan Falls and C J Strike hydro plants are privately owned and operated by the Idaho Power Company, which also serves as the transmission authority for the latter two plants. The transmission authority of Anderson Ranch and Black Canyon hydropower plants falls under the purview of the Bonneville Power Administration. Notably, all four hydropower plants are operated either federally or by the utility responsible for serving communities in the region. Therefore, it can be assumed that the ownership of the hydro facility, transmission interconnection, and dam facility will present little barrier for these plants to operate in microgrids. Anderson Ranch dam has primary purpose of flood control, whereas the other three dams are intended for hydroelectric generation. Based on this analysis, Anderson Ranch hydropower plant is scored 4 out of 5, while the other three obtain the highest score 5 for microgrid formation metric. However, a more in-depth examination of the policies of each ownership entity and regulatory bodies is crucial. Additionally, it is important to understand how non-power considerations related to water resources may impact the ability of hydropower plants to operate effectively within microgrids.

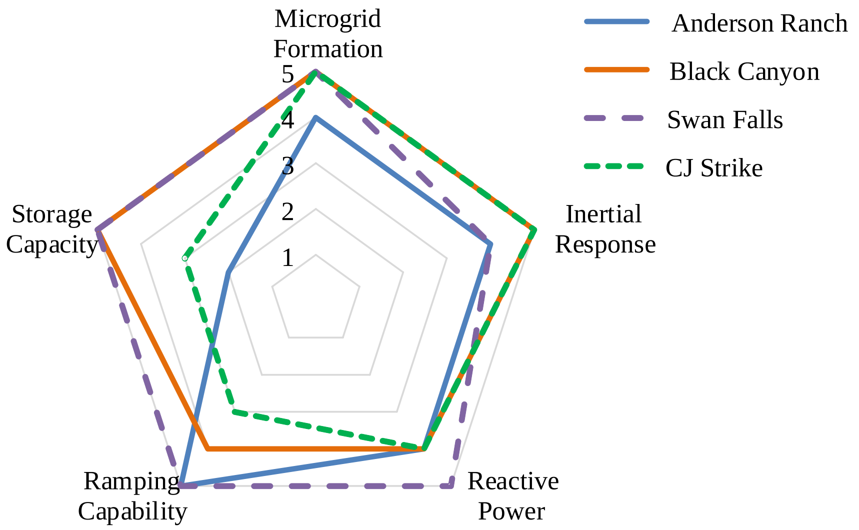

Figure 4: Hydropower Characterization Metric Scores for Four Hydropower Plants in Idaho [Metric scores are depicted on a scale from 1 to 5, with 5 indicating high suitability for resilient microgrids and 1 indicating low suitability]

The remaining four capability metrics are contingent upon electrical, mechanical, control, and reservoir attributes of the hydropower plants. All four hydropower plants have already been assessed suitable for microgrid in terms of their sizes. The size of a plant or the sizes of units in a plant helps determine the size of a microgrid it can feasibly support. To facilitate a relative comparison among hydropower plants of different sizes, these metrics are evaluated on a per MVA basis relative to the plant size.

Reactive power capability metric is primarily evaluated based on the reactive power limits obtained from the PSS/E power flow machine data, along with the exciter control time constant and rate limits specified in exciter models. Based on data in HRD, all four hydropower plants have comparable relative reactive power capacity scoring either 4 or 5 out of 5 in this metric category. The generator characteristic curve that imposes the maximum reactive power capacity during certain real power generation is not considered for this evaluation; however, it should be included in future analyses.

Inertial response depends upon the mass of rotating components within the power plant, quantified in terms of inertial constant obtained from the PSS/E hydrogenator information. All four hydropower plants have strong inertial response capability, scoring either 4 or 5 in this metric category.

Ramping capability is influenced by factors such as water starting time, droop constant, governor time constant, servo motor time constant, pilot valve time constant, and gate opening rate limits, all sourced from PSS/E Hydro-governor information. Based on information complied in HRD, Anderson Ranch and Swan Falls hydropower plants have superior ramping capability compared to Black Canyon and C J Strike hydropower plants, as shown in Figure 4. The storage capacity depends upon the dimensions of the reservoir, the information we obtained from the NID database. Swan Falls and Black Canyon hydro have comparable storage size relative to their plant sizes, both earning the score of 4. C J strike and Anderson Ranch score 3 and 4, respectively, out of a total of 5 in the storage capacity metric category.

Note that the scores provided in Figure 4 are relative to these four hydropower plants. Considering larger subset may change the relative scores in each metric category.

Evaluating these characterization metrics not only allows utilities to promptly identify hydropower plants with the greatest potential for microgrid formation but also helps in comprehending their ability to fulfil essential microgrid functions. As previously discussed, certain hydropower plants might excel in one category while being weaker in another. This analysis also pinpoints areas of weakness where microgrid planners can invest in to enhance the suitability of a hydropower plant for microgrid formation.

6. Conclusion and Future Work

In this paper, we present a framework for the development of a comprehensive HRD and visualization tool to assess hydropower plants' potential in forming microgrids and strengthening grid resilience. By combining data from various reliable sources, including the ORNL HydroSource, the NID, and the US Western Grid stability base cases, we created a valuable resource containing detailed information about hydropower plants in four states of the US: California, Oregon, Washington, and Idaho.

The HRD includes essential parameters related to the hydropower plant, such as capacity, operational mode, unit count, dam dimensions, reservoir capacity, reactive power limits, and ramp rates. An interactive map is developed to visualize HRD using the ArcGIS platform. The interactive map presents different hydropower plants as individual dots, and by hovering over these dots, users can access comprehensive information about each facility. The HRD serves as a crucial tool for stakeholders, including hydropower plant owners, utilities, communities, and microgrid planners, to make data-driven decisions and strategically plan for microgrid deployment in vulnerable regions.

Using HRD, a set of metrics are evaluated to quantify hydropower plant’s ability to operate in microgrids and support essential functions such as reactive power, inertial response, ramping, and energy storage. Assessing these metrics enables utilities to quickly identify high-potential hydropower plants for microgrid formation and understand their capacity to fulfil key microgrid roles, revealing both strengths and weaknesses.

Although this study centered on hydropower plants in wildfire-prone regions, the proposed approach and developed database is equally relevant to enhancing grid resilience in other contexts as well. Considering the capabilities of hydropower plants, the developed HRD can be utilized to assess their contributions in withstanding and recovering from various high-impact low-probability disruptions, such as hurricanes, floods, and other extreme weather events. By exploring the potential of hydropower in enhancing grid resilience against different disaster scenarios, this research can pave the way for resilient planning strategies that strengthen energy infrastructure and ensure reliable power supply in vulnerable regions facing diverse grid challenges.

As a part of the future work, we will conduct develop a framework for impact studies and simulations to evaluate the performance of microgrids formed around selected hydropower resources in disaster-prone regions. Through these simulations, we can assess the effectiveness of microgrid formation in enhancing the resilience of the power grid. The results from these studies will aid in refining microgrid design and operation strategies.

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