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Changing the World's Energy Future

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Hydropower Potential at Non-Powered Dams: A Multi-Criteria Decision Analysis Tool based on Grid, Community, Industry, and Environmental Impacts

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ABSTRACT

Non-powered dams (NPDs) are dams that do not include hydraulic turbine (hydropower) equipment. Currently, there are more than 80,000 such dams in the United States, which provide a variety of non-energy benefits, including flood control, water supply, navigation, and recreation. Approximately 500 of these NPDs are identified as having the potential to add hydropower generation (totaling up to a capacity of more than 8200 MW). A large share of investment costs and environmental impacts of dam construction have already been incurred at these NPDs. Hence, adding power to the existing dam structure is hypothesized to be achieved at a lower cost, with less risk, and a shorter timeframe than the development required for new dam construction. The abundance of NPDs, the associated environmental favorability, and cost advantages, combined with the reliability, predictability, and dispatchability of hydropower, make NPDs a strong candidate in the nation's renewable energy portfolio. To assess the NPD to hydropower conversion potential, in this study, we developed a GIS-based multi-criterial decision analysis tool, which allows users to rank these NPDs based on the grid, community, industry, and environmental impacts (i.e., GCIE impacts). This web-based interactive tool (developed using open-source Python and JavaScript) lets the user choose from a wide range of features to define each of the GCIE impact scores through a user-friendly graphical user interface. These features are related to dam operation, hydropower generation opportunity, power market economy, social vulnerability and risk, proximity to critical infrastructure and energy generating facilities, environmental concerns (air, water, and critical habitat), and exposure to natural hazards. The overall priority score of NPDs is calculated based on user-defined weights for each of the GCIE impact scores. Besides ranking NPDs, the tool can also be used to estimate the energy-storage feasibility (battery, hydrogen, and pump-storage hydropower) at each of the potential sites.

1. INTRODUCTION

There is a relatively large amount of untapped potential to increase the amount of hydropower energy generated by powering non-powered dams (NPDs) in the United States. Considering that only 3% of the nation's dams (~80,000 total) are powered (Fitzgerald, 2022), and the largest costs of hydropower development typically come from the construction of the dam, NPDs offer a significant opportunity for renewable energy deployment, considering that even just the top 500 potential sites for conversion have over 8200 MW of aggregate potential capacity (Hansen et al., 2022). As of 2019, 93% of the proposed hydropower capacity in the United States came from powering NPDs and expanding existing powered facilities (Uria-Martinez et al., 2021). There is additional motivation for converting NPDs because of the nationwide goal to reach net-zero carbon emissions by 2050 (Kerry, 2021). To assess NPD conversion potential, our team has developed a tool that allows stakeholders to evaluate and identify, on a national scale, which NPDs best suit their criteria to be converted to powered dams (PDs).

As identified by Hansen et al. (2021), contemporary assessment tools for NPD development do not fully consider all stakeholder needs. Currently, decisions on hydropower conversion of NPDs rely on traditional financial metrics, like return on investment and payback periods. As hydropower is a long-lived asset with a relatively high initial investment and sometimes lengthy permitting processes, it can be a challenging opportunity for the private sector. However, there may be potential community and societal benefits that can motivate investment in such projects, particularly if one can leverage energy storage technologies to mitigate environmental impacts. Current dam characteristics are important factors in predicting opportunities for improved environmental conditions, grid improvements, and community and industry benefits. It is important to assess which sites might be most likely to see different benefits so that stakeholders, such as developers, technology providers, and communities, can identify opportunities they want to analyze or explore. Existing public software for NPD analysis enables the visualization and collation of a wide range of data related to NPDs (ORNL, 2022). While these tools offer incredible amounts of data, they do not easily allow for the prioritization of sites based on different criteria, nor do they include some key data points that may be relevant to grid, community, industry, and environmental impacts (i.e., GCIE impacts). They also do not consider data relevant to the feasibility of adding innovative technology such as energy storage through batteries, hydrogen production, or pumped storage hydropower (PSH). As increasing amounts of renewables are added to our grid, energy storage technologies may be particularly interesting for stakeholders to explore along with energy generation at NPD sites.

The core capability and strength of our NPD tool is the ability to prioritize NPD sites based on scores for potential GCIE impacts, including battery, PSH, and hydrogen production feasibility. The tool includes information regarding the features that make up each score which facilitates transparency and helps stakeholders fully understand their selections. To enable greater flexibility in usage, the user can select which features they want to include in each GCIE score calculation. The grid, community, industry, and environmental scores can also be weighted on a scale between 0-1 (0 - lower priority, 1 - higher priority) and stakeholders can adjust the weights based on their preferences to identify sites that may be worth further analysis. This tool builds on previous NPD databases by allowing stakeholders to consider and prioritize a wide range of potential benefits from powering NPDs and identify sites that best fit stakeholder needs. While this tool helps prioritize sites for consideration (at a national level), it is not intended to perform the detailed site-specific analysis needed for development.

This paper focuses on the data processing, tool development & deployment, and potential application of the tool. Section 2 provides the data and methodology for the impact categories (i.e., GCIE impacts) and energy storage feasibility quantification. In Section 3, we provide a brief description of the database development and tool deployment architecture. Section 4 illustrates two use cases of the tool with a focus on grid and community benefits. In Section 5, we provide our concluding remarks and future development potentials.

2. DATA AND METHODS

In the following subsections, we briefly explain the features that contribute to each of the GCIE impact scores. All data related to dam operation and hydropower generation opportunity were obtained from the National Inventory of Dams and ORNL's Non-powered Dam Characteristics Inventory datasets (a total of 498 NPDs were considered in this study each with a potential capacity of at least 1 MW). Energy-related data (e.g., price and consumption) were obtained from the U.S. Energy Information Administration online repositories. Locations and metadata of critical infrastructure (including public schools, hospitals, energy generating facilities, and natural gas compressor stations) were obtained from the Homeland Infrastructure Foundation-Level Data. Data related to air quality, water quality, and critical habitat were obtained from the U.S. EPA, USGS, USFWS, and NOAA.

Grid Impact: The grid impact score is intended to provide a quantitative measure of the potential positive impact that electrifying a particular NPD would have on the electric grid in its vicinity. A list of core grid metrics/data was chosen from the overall available datasets to be included in the grid impact score, including potential generation capacity, distance from NPD to the nearest electric substation, regional hourly peak load, proximity to energy-intensive facilities, and regional average retail price of electricity. The individual scores for each of these metrics are summed (i.e., normalized sum) to generate the overall grid impact score for each NPD being evaluated in the tool.

Community Impact: The community impact score was designed to measure the potential social, economic, public health, and resilience impacts NPD electrification could have on the local community (e.g., within the county or a certain distance) near a particular NPD. Metrics contributing to a dam's community impact score were an area's overall risk of impacts from extreme weather or other climate impacts (i.e., natural hazards), indicating a higher potential resilience value for NPD electrification; the presence and number of local policies that incentivize hydropower or include hydropower in clean energy goals; the percentage of fossil fuel capacity (i.e., the cumulative operating capacity of nearby fossil fuel generation plants) to be replaced; local air quality, measured as a normalized sum of pollutants tracked in the EPA's EJSCREEN database; average residential energy burdens; proximity to schools and hospitals; and the community's score on the CDC's social vulnerability index. Although not included as part of the community impact score, the user also has the option to include or exclude NPDs based on the dam's risk of failure (based on its condition) and risk of downstream flooding (i.e., the severity of flood impact).

Industry Impact: The industry impact score is intended to provide a quantitative measure of the potential positive impact that electrifying a particular NPD would have on the surrounding industries. Specifically considered in this scoring category were industries that are considered to be energy intensive, such as steel production, mining, agriculture, chemical manufacturing, automotive manufacturing, etc. The core metrics/datasets that make up the industry impact score include energy-intensive industry locations, regional average retail price of electricity, potential generation capacity, and distance from NPD to the nearest electric substation. The individual scores for each of these metrics are summed (i.e., normalized sum) to generate the overall industry impact score for each NPD being evaluated in the tool.

Environmental Impact: The environmental impact score was developed to quantify the potential environmental effect of converting an NPD. The score considers the potential for fish passage facilities to be required as part of converting the NPD, the number of oceanic and inland species present in the watershed, local air quality based on EPA's EJSCREEN database, the percentage of fossil fuel capacity (i.e., the cumulative operating capacity of nearby fossil fuel generation plants) to be replaced, and the National Anthropogenic Barrier Dataset score for consideration of dam removal. Although not included as part of the environmental impact score, the user also has the option to include or exclude NPDs located within a habitat designated as critical for species listed as threatened or endangered under the Endangered Species Act.

Energy Storage Feasibility: Adding generation and storage together at NPDs can maximize the opportunities and benefits associated with NPD conversion. Adding energy storage to converted NPDs can directly benefit the electric utilities, neighboring industries, and the overall surrounding community. Choosing one form of energy storage over another depends on several factors, including existing flow releases/rule curves at the dam, technology maturity, cost, scalability, and services most useful to the communities surrounding the NPD. In our work, we considered batteries, hydrogen, and PSH to pair with existing NPDs because of their scalability and high level of technology maturity.

Batteries allow a converted NPD to generate electricity and store it for later use (when it is most needed), but without the physical infrastructure or topographical conditions needed for PSH. When connected to the grid, batteries are used to meet the peak load demand and provide ancillary grid services like scheduling and dispatch, reactive power, voltage control, frequency regulation, load following, and backup power. In this work, battery feasibility considers potential generation capacity and distance to the substation as main features. These two features are directly related to the $/MW connection to the grid (MISO, 2021). Moreover, battery feasibility in this tool is also dependent on proximity to industries, medical facilities, energy demand, and regional retail price of electricity.

Hydrogen production has been used at varying levels of maturity all around the world for various purposes, emphasizing the versatility of this energy storage option. Southern California Gas Company (SoCalGas) and San Diego Gas & Electric Company (SDG&E) have demonstrated a natural gas/hydrogen blending program to help reduce carbon dioxide (CO_2) emissions, the first step in California's plan to inject hydrogen as part of their decarbonization efforts. Hydrogen feasibility in this tool considers the amount of hydrogen production per year (hydrogen generation is directly proportional to the dam's generation capacity and capacity factor), proximity to industries, medical facilities, and natural gas compressing stations, and states that have a high price of electricity.

PSH is very mature and can take several forms. The pumping feature can be used during periods when the electricity prices are low to store the potential energy of the water so that it can be used for generation during periods when electricity prices are higher. PSH feasibility considers impoundment type structure (based on elevation differences between coupled reservoirs), proximity to the substation and energy-intensive industries, the retail price in the region, and critical habitat for threatened/endangered species.

3. DATABASE DEVELOPMENT AND TOOL DEPLOYMENT

Database Development: Based on the obtained data from multiple sources, a compiled database was produced that includes all the features used in the calculation of GCIE impact scores and storage feasibility. Regional and local data were reduced down to site-scale data. An example of such data reduction is the assignment of state-wide electricity retail price to all the NPDs located within the state boundary. Another example of data reduction is the assignment of county-specific CDC social vulnerability index to all the NPDs located within the county. Joint geospatial data were produced by creating an association between one vector data layer to another. For example, the proximity to hospitals was calculated by counting the total number of hospitals within a 50-mile radius around each of the NPD sites (the 50-mile radius threshold was determined based on stakeholder interviews not included in this paper). Another example of joint geospatial association is the calculation of the capacity of nearby fossil fuel power plants, where the total operating capacity of all the fossil fuel power plants within a 50-mile radius was summed up (Figure 1). These calculations were conducted using the *ArcPy* package of ESRI's ArcGIS Pro Python API.

Besides the compiled NPD dataset with all the features required to calculate the impact scores and storage feasibility at each NPD, the database also contains vector data of all the underlying features that contributed to the score calculations. Examples of such vector data are state-wide retail price of electricity, county-specific social vulnerability index, and locations of critical infrastructure such as hospitals and public schools. All these vector layers (including points, lines, and polygons) were stored in a geodatabase (i.e., **.gdb*) as separate feature classes (Figure 1). These additional vector data layers can be enabled within the tool to help visualize the geospatial relationships with each NPD.

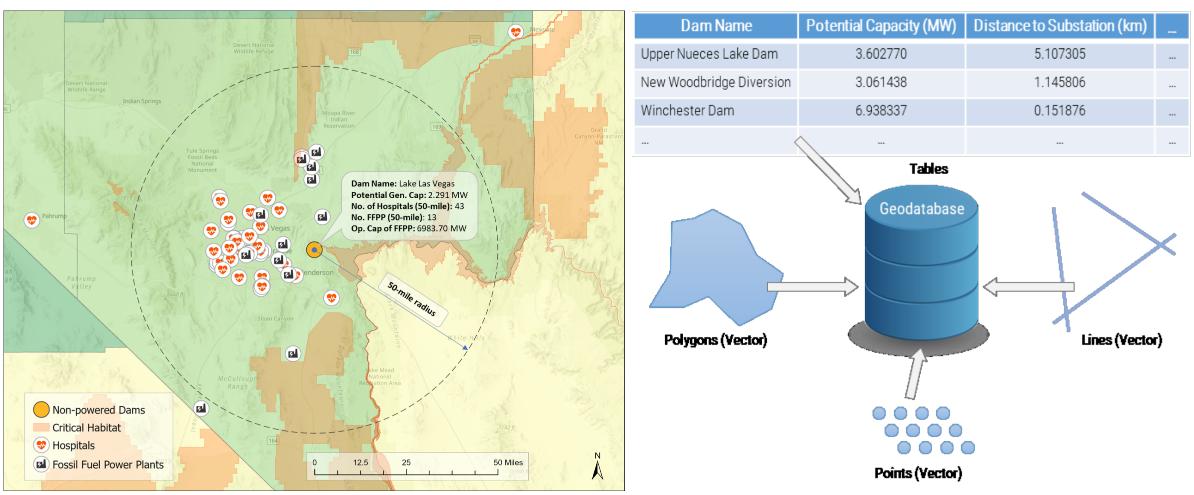

Figure 1: (Left) Example of geospatial association process between NPD and its surrounding hospitals and fossil fuel power plants (within a 50-mile radius). (Right) a schematic diagram showing the system architecture of the geodatabase.

Tool Development: The tool itself is a software product composed of multiple independent services. Being a full-stack application, the tool is comprised of a user interface, a server application, and a database. Together, these services accomplish the range of features required for NPD exploration and scoring. The following (Figure 2) is an overview of the software architecture used to develop the tool.

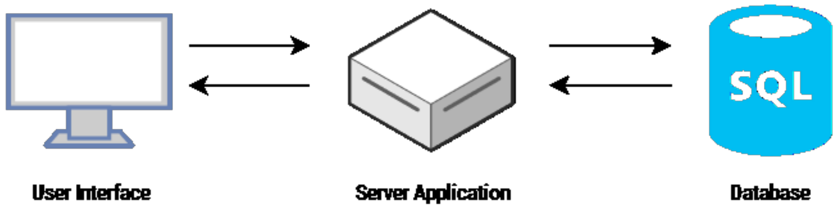

Figure 2: The user interface of the tool is used for exploring NPD candidates on a map through a web browser. This interface makes calls to a server application, which queries the database for NPDs. The server application then scores the NPDs according to user inputs (e.g., category weight and features considered) and returns them to the user interface.

User Interface: The user interface is developed using the *React* framework. This framework enables rapid development of software tools and also leverages component libraries, which provide developers with useful components like drop-downs, checkboxes, and sliders.

Server Application: There is a multitude of server frameworks available for tool development, but the *Django* framework was selected for its ease-of-development, and availability of database management features.

Database: The NPD database exists in the form of a geodatabase (i.e., **.gdb*), which stores data in a tabular format, much like any other relational database. The *Postgres* database, with the *PostGIS* extension enabled, was selected as the database provider for the tool. *Postgres* is selected for its ability to handle spatial data, interpreting geodatabase shapes as *point*, *polygon*, and *multi-polygon* data types.

Deployment of the tool is made possible through the Idaho National Laboratory's cloud infrastructure. The docker containers composing each of the individual components of the tool are published to a container repository, which is then sourced for deployment onto a Kubernetes cluster. This modern deployment pipeline leverages best practices that automate infrastructure management, maximize security, and enable any software engineer to reproduce the application locally to make and publish code changes.

4. USE CASES

We demonstrate the capabilities of the tool through two hypothetical use cases in which imagined users utilize the tool according to their respective priorities and goals.

Use Case 1: In the first use case, we created a scenario in which a user selects a higher priority for the community impact score (assigning the weight to 1.0) and a relatively lower priority to the rest of the scores (assigning 0.25 to grid, industry, and environment). We also kept all the features selected as default. The following figure (Figure 3) shows the top 10 candidates for hydropower conversion in green based on the defined weights. We see eight of the top 10 potential sites in the northeastern United States (one in New Jersey, three in New York, and four in Pennsylvania). The remaining two are in Texas and California (Figure 3). The top 100 candidates are shown in yellow, while the rest of the NPDs are shown in orange. The best candidate, in terms of the total score, was the New Croton Reservoir Dam located in Westchester county, New York, with a potential capacity of 8.79 MW (Figure 3).

It is important to note that these top 10 candidates are ranked based on the total score, which is a linearized sum of all the individual GCIE impact scores multiplied by their assigned weights. In this scenario, since the community impact score was assigned a higher priority compared to the rest, the total score (hence the overall ranking) was dominated by the community score calculated through the default features. We also see the potential of battery storage and hydrogen production feasibility for each of these NPD sites in the table below the map (Figure 3). The majority of the top 10 candidates have a high potential for both battery storage and hydrogen production feasibility. The table also shows different land use restrictions such as critical habitat, protected land, and impaired stream status. By default, the table shows the top 10 candidates, however, other sites can also be explored by scrolling through the table. Besides, the tool has the option to export the entire database in a tabulated format (without the GCIE impact scores since they are calculated based on the user-assigned weights) with descriptions of columns and other metadata information.

Use Case 2: In the second use case, we created a scenario with a higher priority on the grid impact score (assigning the weight to 1.0) and the least possible priority to the rest of the scores (assigning 0.0 to community, industry, and environment). We also modified the feature selection under the grid benefits (Figure 4). Instead of selecting all the default features, we only selected potential capacity and proximity to the substation as the contributing features in the grid impact score calculation. The following figure (Figure 4) shows the top 10 candidates for hydropower conversion in green based on the defined weights and selected features. Out of the top 10 candidates, two are located in Alabama, three in Arkansas, one in Illinois, three in Kentucky, and one in Missouri (Figure 4). The top 100 candidates are shown in yellow, while the rest of the NPDs are shown in orange. The best candidate, in terms of the total score, was the Ohio River Locks & Dam 52, located in McCracken county, Kentucky, with a potential capacity of 494.51 MW and the nearest substation located approximately 4 kilometers (2.5 miles) away (Figure 4).

Similar to the previous use case, the top 10 candidates are ranked based on the total score, which is a linearized sum of all the individual GCIE impact scores multiplied by their assigned weights. In this scenario, since the grid impact score was assigned a higher priority compared to the rest, the total score (hence the overall ranking) was dominated by the grid score calculated through the selected features. Besides the battery storage and hydrogen production feasibility and several land use restriction statuses, we also see the potential generation capacity and distance to the nearest substation in the table below the map for the top 10 candidates. As mentioned earlier, by default, the table shows the top 10 candidates, however, other sites can also be explored by scrolling through the table.

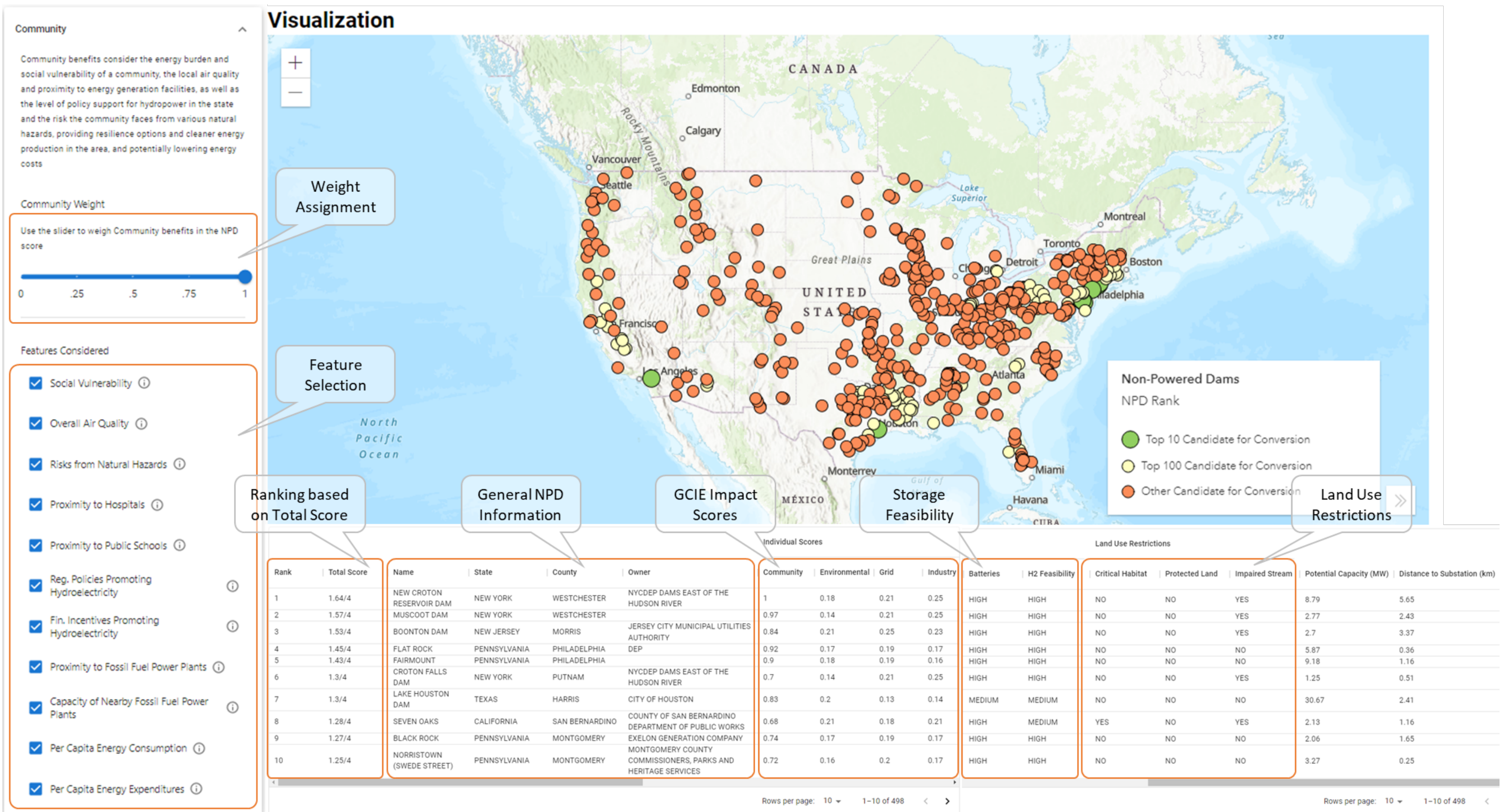

Figure 3: A generic interface of the tool with the community score weight assignment and feature selection options on the left panel, results on the map in the middle, and an attributes table below the map. The results shown represent use case 1 (i.e., dominated by the community impact score).

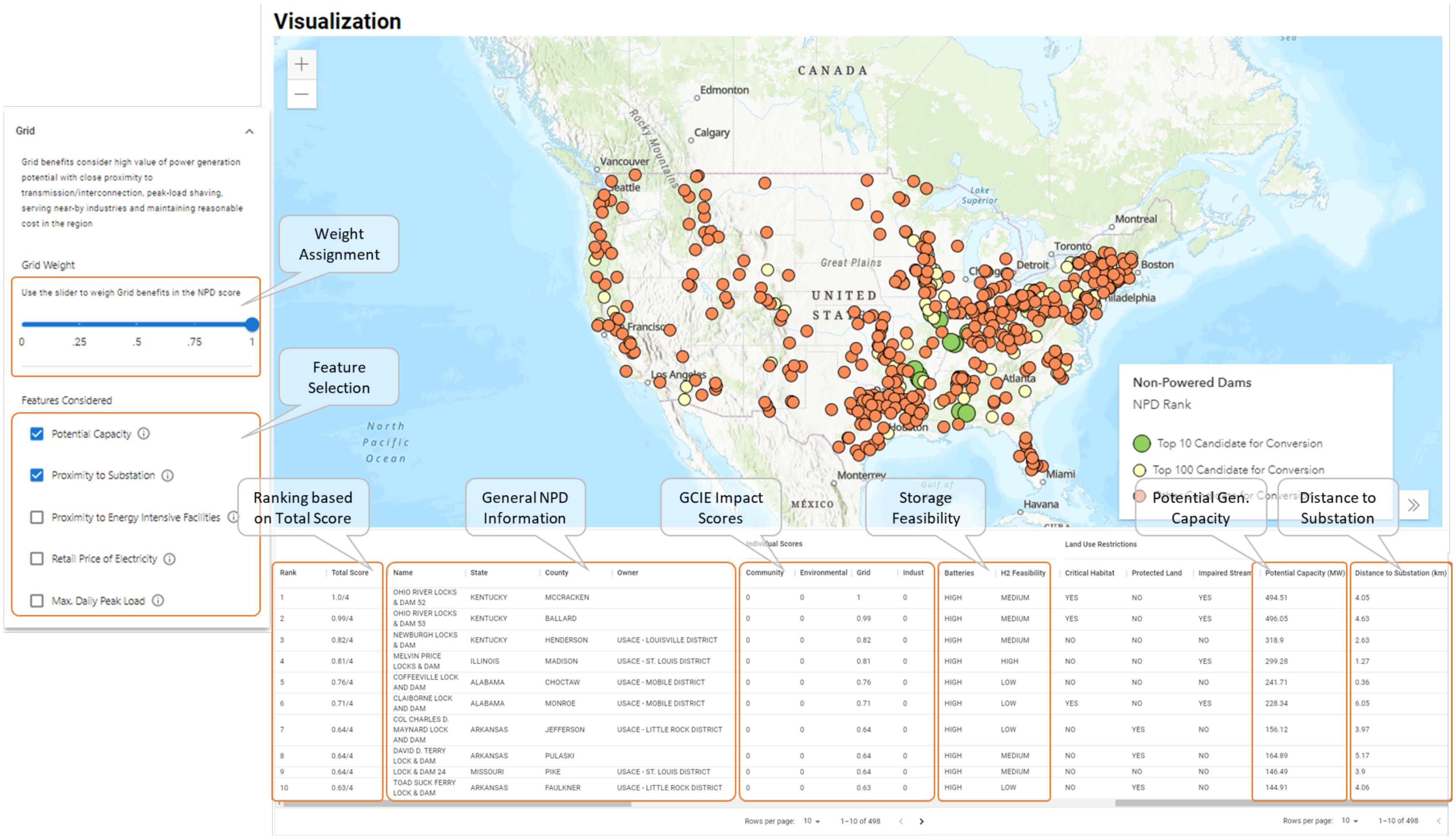

Figure 4: A generic interface of the tool with the grid score weight assignment and feature selection options on the left panel, results on the map in the middle, and an attributes table below the map. The results shown represent use case 2 (i.e., dominated by the grid impact score).

5. CONCLUSIONS

In this study, we developed a GIS-based online tool that allows users to prioritize existing NPDs in terms of grid, community, industry, and environmental benefits (through GCIE impact scores) stemming from the NPD to hydropower plant conversion. The tool also provides a qualitative measure of several energy storage feasibilities including battery storage and hydrogen production. The need for such a development effort was felt due to the absence of user-friendly tools that allow prioritization of potential NPD sites based on a wide array of impacts (i.e., GCIE impacts) and innovative technology retrofits. In our developed tool, based on the users' interest, the impact scores and their contributing features can be easily adjusted to create various scenarios that can help stakeholders in conducting a multi-criteria decision analysis. We have highlighted the user-friendliness and interactively of the tool with two use cases focusing on community and grid benefits. The tool is intended to be used as a national-level prioritization tool instead of a site-specific assessment tool. For site-specific analysis, we recommend a more robust approach with dynamic models representing each of the involved systems. In future endeavors, we plan to develop site-specific tools for more advanced users and research communities.

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