Figure 1. Aerial view of Gavins Point dam and power-house
(source: Omaha District Hydropower Master Plan August 2016)
Project Overview

Project Summary

Understanding how hydropower operates in response to the underlying uncertainties with respect to the system constraints is crucial in identifying its operational flexibility potentials. In this project, the flexibility of the operating hydropower facility is described by capturing uncertainties in both water and power system and formulating the operations as a multistage stochastic Optimization problem. The proposed approach supports short to seasonal-term operations and planning decision horizons. First, assimilate the uncertainties for future scenario generation and validate the corresponding scenario tree. Second, analyze the structure of mathematical model the role and contributions of incorporated constraints.

Intended Outcomes

• Provide a decision support framework which can quantify potential flexibility scenarios for existing hydropower systems to meet the requirement of the future grid.
  ✓ Operational flexible strategies under different scenarios, to provide actionable decisions under uncertainty;
• The framework is intended for use by Engineer Research and Development Center (ERDC) of the U.S. Army Corps of Engineers (USACE) for the water management facilities within the USACE’s operational responsibility.
• Provide training opportunities for two early career scientists and two Ph.D. graduate student.
Project Objectives: Relevance

The mission of the HydroWIRES (Water Innovation for a Resilient Electricity System) Initiative is to understand, enable, and improve hydropower’s contributions to reliability, resilience, and integration in the rapidly evolving U.S. electricity system.

Relevance to Program Goals:

Account for and optimally trade-off among multiple operational, environmental and regulatory constraint that regulates hydropower facilities in the United States.

- Develop a framework for identifying potential flexibilities for hydropower operations in presence of net-load and inflow uncertainty.
- Identifying how each constraints contribute to operational flexibility through assessing the optimal strategies,
- Develop a probabilistic structure that represents joint inflow and net-load future scenarios as the input to the designed decision-making optimization algorithm.
  - Find optimal operational strategies for the hydropower facility for it to contribute to the electric grid planning and operations with its utmost potential in flexibility.
Project Objectives: Approach

Approach:

Generally, hydropower contributions to system flexibility is modeled only through its helping hand to the variable generation and does not incorporate the interactions between different sources of generation. Therefore, the potential strategies for more flexible operation is not addressed. Our proposed framework tackles these gaps through:

- Uncertainty analysis & design and solution of stochastic optimization.
- Developing a set of optimal operational strategies of highly flexible hydropower facilities given the operational, environmental and electric grid related constraints.

The proposed framework is innovative in comprehensive modeling of hydropower operation that both unveils the hidden flexibility capabilities in an existing operating system and identifies the flexibility potentials that are expected to emerge under variable generation especially in modernized grid.
Project Objectives: Expected Outputs and Intended Outcomes

**Outputs:**
Addressing efficient reservoir operation, considering underlying physical and engineering characteristics of the system, through:
- Multivariate scenario tree generation algorithm,
- Streamflow and Net-load joint scenario trees,
- Multistage stochastic optimization model
- A framework for analyzing optimal decision scenarios
- Reports and deliverables
  - Quarterly reports
  - Critical Design Review reports (Year I)
  - Scientific publications (journal and poster)
    - AGU Conference presentations (Fall meetings 2020 and 2021)
    - Collaboration with PNNL on Flexibility framework

**Outcomes:**
- Provide a decision support framework which can quantify potential flexibility scenarios for existing hydropower systems to meet future grid loads.
- The framework is intended for use by Engineer Research and Development Center (ERDC) of the U.S. Army Corps of Engineers (USACE) for the water management facilities within the USACE’s operational responsibility.
- Provide training opportunities for two early career scientists and two Ph.D. graduate student.
Project Timeline

**2020**

<table>
<thead>
<tr>
<th>Task</th>
<th>Duration</th>
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<tbody>
<tr>
<td>1a.</td>
<td>Jul 1 - Dec 31</td>
</tr>
<tr>
<td>1b.</td>
<td>Jul 1 - Mar 31</td>
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<tr>
<td>1c.</td>
<td>Jul 1 - Mar 31</td>
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**2021**

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<tr>
<td>2b.</td>
<td>Oct 1 - Jun 30</td>
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**2022**

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<td>Oct 1 - Jun 30</td>
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<tr>
<td>3b.</td>
<td>Jan 1 - Jun 30</td>
</tr>
<tr>
<td>3c.</td>
<td>Oct 1 - Jun 30</td>
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**2023**

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<tr>
<td>4b.</td>
<td>Jan 1 - Jun 30</td>
</tr>
<tr>
<td>5a.</td>
<td>Jan 1 - Jun 30</td>
</tr>
<tr>
<td>5b.</td>
<td>Jan 1 - Jun 30</td>
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</table>

Go / No-Go

1. Is the Mathematical model of hydropower operation developed? YES → GO
2. Has the model structure been analyzed, and the conflicting constraints identified? YES → GO
3. Is the developed scenario tree generation framework validated? YES → GO

Q3 (Y1Q1) | Q4 (Y1Q2) | Q1 (Y1Q3) | Q2 (Y1Q4) | Q3 (Y2Q1) | Q4 (Y2Q2) | Q1 (Y2Q3) | Q2 (Y2Q4) | Q3 (Y3Q1) | Q4 (Y3Q2) | Q1 (Y3Q3) | Q2 (Y3Q4)

Task 1

- 1a. Construct the customized set of constraint
  - Jul 1 - Dec 31
  - 1b. Select hydropower facility for the case study
  - 1c. Assimilate and regionalize net-load and streamflow data

Task 2

- 2a. Develop the optimization algorithm
  - Oct 1 - Jun 30
  - 2b. Develop a scenario tree generation framework
  - Oct 1 - Jun 30

Task 3

- 3a. Analyze the mathematical program structure
  - Oct 1 - Jun 30
  - 3b. Develop trade-off strategies for each constraint
  - Jan 1 - Jun 30
  - 3c. Categorize the trade-off strategies within the grid
  - Oct 1 - Jun 30

Task 4

- 4a. Define measures to quantify flexible operation
  - Jul 1 - Dec 31
  - 4b. Sensitivity analysis with respect to uncertainty
  - Jan 1 - Jun 30

Task 5

- 5a. Ex-post and ex-ante analysis of operational flexibility scenarios
  - Jan 1 - Jun 30
  - 5b. Evaluate EVPI and VSS measures
  - Jan 1 - Jun 30
## Project Budget

### Total Project Budget – Award Information

<table>
<thead>
<tr>
<th>DOE</th>
<th>Cost-share</th>
<th>Total</th>
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<tr>
<td>$872.3K</td>
<td>$218.1K</td>
<td>$1090.4K</td>
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</table>

<table>
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<tr>
<th>FY20</th>
<th>FY21</th>
<th>Total Actual Costs FY20–FY21</th>
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<tbody>
<tr>
<td>Costed</td>
<td>Costed</td>
<td>Total Costed</td>
</tr>
<tr>
<td>$169.4K</td>
<td>$335.4K</td>
<td>$504.8K</td>
</tr>
</tbody>
</table>

![Bar chart showing costs for each quarter from Y1Q1 to Y2Q4]
End-User Engagement and Dissemination

The project provides a decision support framework:

- Reveal potential flexibility of existing hydropower systems
- ERDC can help play a role in dissemination of these capabilities to the water management community within the USACE.

Our research team is in close communication and collaboration with Missouri River Basin Water Management Division:

- Obtained water system data (time series of mainstream, powerhouse, spill, total Release, energy, evaporation, etc. historical data.
- Monthly meetings to communicate and discuss the results.

U.S. Army Corps of Engineers (USACE), Engineer Research and Development Center (ERDC) Costal and Hydraulic Laboratory has endorsed and supports this project.

- The USACE owns and operates hundreds of reservoirs with various characteristics and functionalities across the CONUS.
- The ERDC is interested in investigating new and emerging technologies for potential application to the field within the USACE.
- This research is of interest to USACE personnel who make operational decisions.
Demonstrating the proof of concept by developing baseline components of the proposed approach:

- A hydropower operation model (multistage stochastic optimization) is developed.
  - The system constraints are studied and included in the optimization model,
- Joint net-load and inflow scenario tree generation algorithm is developed and validated.
  - Analyze and create regionalized net-load and streamflow scenarios,
- Stochastic dual dynamic programming is employed as the solution algorithm.
- The flexibility metric is defined.
- Scientific performance:
  - Two Presentations at American Geophysical Union (AGU) Fall meetings 2020 and 2021 in the Forecast-Informed Reservoir Operations session.
  - Ongoing collaboration with PNNL on the flexibility framework
Performance: Accomplishments and Progress

- The Missouri River Basin Reservoir water control master plan for the whole reservoir system is reviewed and the set of constraints based on which the system operated is derived and to be included and analyzed in the mathematical model through out the projects. Our research team have also obtained and analyzed, water system from the U.S. Army Corps of Engineers and Missouri River Basin Water Management and part of the requested power system data from Western Area Power Administration.

The six System dams are regulated as a hydraulically and electrically integrated system for the Congressionally authorized purposes of:
- flood control, navigation, hydropower, water supply, water quality control, irrigation, recreation, and fish and wildlife.

Table 1. Hydropower Generation Statistics

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Installed Capacity (MW)</th>
<th>Annual Generation (GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fort Peck</td>
<td>185.0</td>
<td>1,048</td>
</tr>
<tr>
<td>Garrison</td>
<td>583.3</td>
<td>2,250</td>
</tr>
<tr>
<td>Oahe</td>
<td>786.0</td>
<td>2,621</td>
</tr>
<tr>
<td>Big Bend</td>
<td>494.0</td>
<td>969</td>
</tr>
<tr>
<td>Fort Randal</td>
<td>320.0</td>
<td>1,727</td>
</tr>
<tr>
<td>Gavins Point</td>
<td>132.0</td>
<td>727</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2,500.3</strong></td>
<td><strong>9,342</strong></td>
</tr>
</tbody>
</table>
The multistage stochastic optimization is formulated to model the operation of Missouri River Mainstream reservoirs under net-load and inflow uncertainty.

- Hydropower planning and operation is a decision-making process:
  - Under uncertainty due to the unknown parameters such as natural inflows to the reservoirs, future load demands, renewable generation fluctuations, ...
  - Multi-period optimization problem since the decisions must be taken in a sequential manner.

![Figure 4. Schematic of decision nodes on a policy graph](image)

![Figure 5. Missouri River Basin system constraints](image)
A multivariate scenario tree generation algorithm is implemented to generate the probabilistic structure of underlying uncertainties as a baseline input to the optimization model.

- Tree is a directed graph (Nodes and Edges)
- Each node has a corresponding vector of values (inflow & net-load)
- The present is deterministic and is the root of the tree,
- The edges connect the parent node to its successors,
- The probability law:
  - Associates to each edge a conditional probability of the outcome given the unique path ($\pi_0 = 1$)
  - Recursive rule
- A solution is a policy.

Figure 6. A scenario tree starting from a known state at root node $t = 0$ i.e., present state and splitting off at $t = 1$ and $t = 2$ to account for multiple possible futures.

Figure 7: (left) Historical daily streamflow trajectories for first week of May. (right) Corresponding scenario tree with branching structure [1 2 2 2 2 2 1]
• Year 2020 streamflow trajectories (blue line) are used to represent the future, (training data: 1967-2019)
• The quality of approximation can be measured by how enclosed is the blue line within the tree.

Figure 8: Monthly streamflow scenario trees for Gavins Point
In order to solve the optimization problem, the solution algorithm in the form of stochastic dual dynamic program is implemented in Julia, a package for solving large multistage convex stochastic programming problems. The methodology can find a flexible range of operational scenarios for each decision variable.
Performance: Accomplishments and Progress

- **Flexibility Metric**
  - The water availability scenarios capture the uncertainty in the inflows that modulate flexibility in the facility,
  - The net load scenarios, on the other hand, capture the uncertainty and constrain the flexibility in the facility.

**Flexibility**: Measurable function of joint inflow and net-load distribution.

\[
f: X \rightarrow Y
\]

\[
\forall R \in \sigma(Y), \exists \text{pre - image in } \sigma(X)
\]

\[
f^{-1}(R) := \{x \in X: f(x) \in R\}
\]

- **X**: Discrete state of the system
- **Y**: Optimal solution space
Performance: Accomplishments and Progress

• Structure of Electric Balancing Authorities (BA) in the Missouri River Basin to obtain regionalize net-load data

• Reservoirs of interest span two BAs:
  • WAPA Upper Great Plains West (Fort Peck)
  • Southwest Power Pool (All others)

• SWPP load is mostly met with internal generation, minimal interchange

• WAUW has constant interchange with three other BAs, meaning that the net load signal for Fort Peck must account for the weighted behavior of each of these BAs.

Figure 9: Hourly power generation portfolio
Future Work

The overall goal in future performance periods is to apply the developed concept in a real operational scale for the Missouri River Mainstream Reservoir System:

• Consult with our collaborators in Missouri River Basin Water Management to extend the current implemented optimization model to a real and reasonable operational decision horizon.
• Generate and validate the new multivariate scenario trees (based on the regionalized net-load and streamflow scenarios) to be employed as the baseline probability models.
• Through analyzing the structure of mathematical model, the role and contribution of incorporated constraints in operational flexibility of the system are identified.
• By utilizing Holistic Grid Resource Integration and Deployment (HiGRID) tool, the types of ramping events in the net-load that will need to be satisfied under scenarios of increasing renewable energy penetration are identified.