Award Number : DE-EE0008943
Identifying Hydropower Operational Flexibilities in Presence of Streamflow and Net-load Uncertainty

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

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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 Information

Principal Investigator(s)

- Dr. Soroosh Sorooshian (PI)
- Dr. Kuolin Hsu (Co-PI)

Project Partners/Subs

- UCI- Advanced Power and Energy Program (APEP)
- Dr. Scott Samuelsen (Co-PI)
- Dr. Brian Tarroja (Co-PI)

Project Status

Ongoing

Project Duration

- Project Start Date 07/01/2020
- Project End Date 06/30/2023

Total Costed (FY20–FY21)

$504.8K

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.

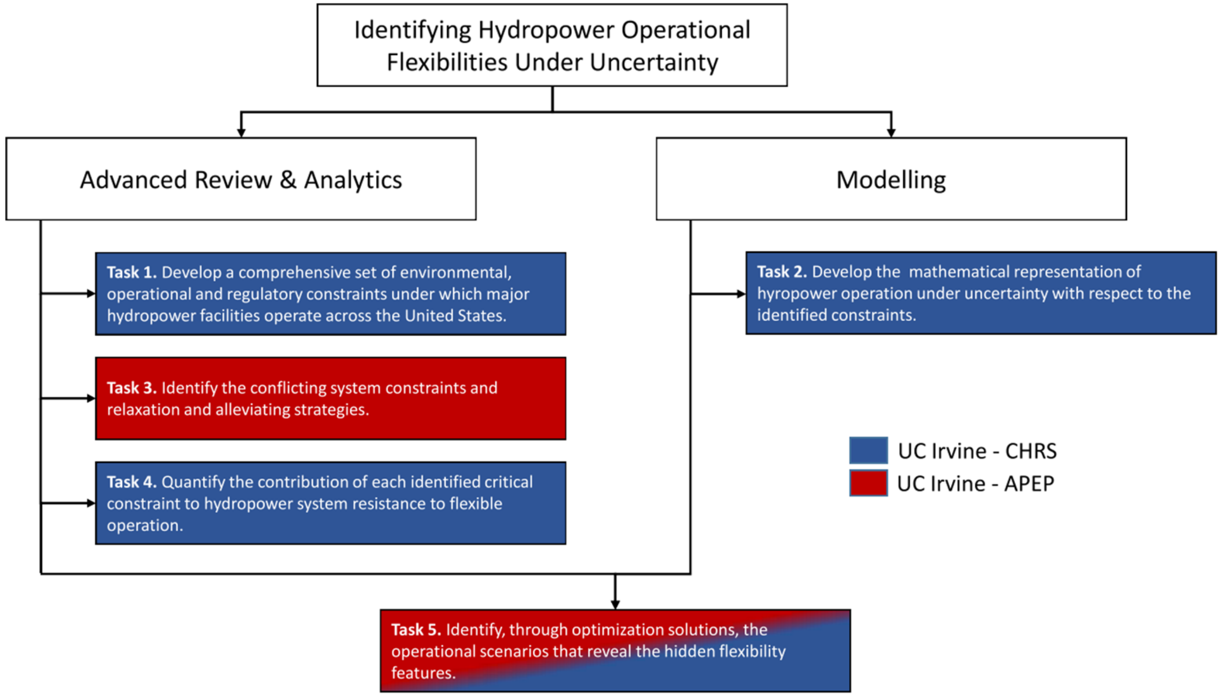


Figure 2. Technical Workflow

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

Go / No-Go (end of Q2 (Y1Q4), 2021)

Go / No-Go (end of Q2 (Y2Q4), 2022)

2020		2021				2022				2023	
Q3 (Y1Q1)	Q4 (Y1Q2)	Q1 (Y1Q3)	Q2 (Y1Q4)	Q3 (Y2Q1)	Q4 (Y2Q2)	Q1 (Y2Q3)	Q2 (Y2Q4)	Q3 (Y3Q1)	Q4 (Y3Q2)	Q1 (Y3Q3)	Q2 (Y3Q4)

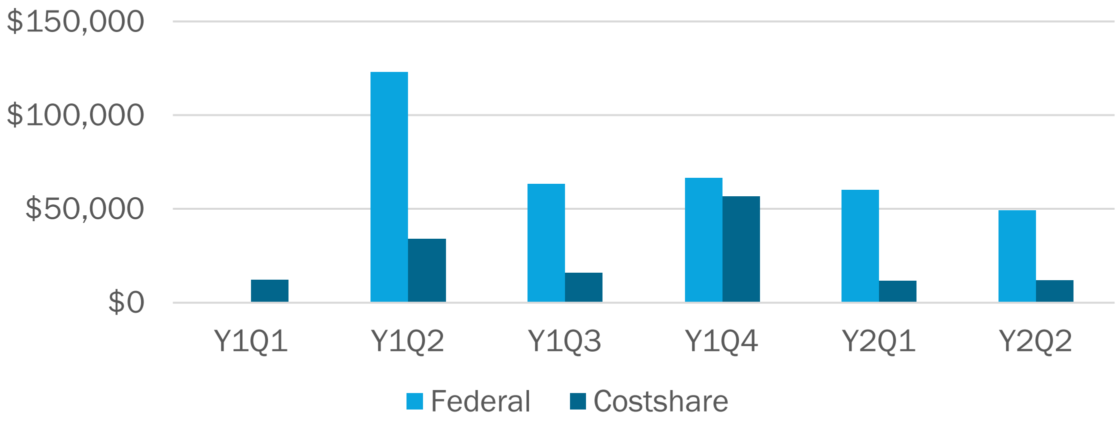
1. Is the Mathematical model of hydropower operation developed? YES → GO
2. Has the model structure been analyzed, and the conflicting constraints identified? YES → GO
3. Is the developed scenario tree generation framework validated? YES → GO

Task 1	1a. Construct the customized set of constraint	Jul 1 - Dec 31
	1b. Select hydropower facility for the case study	Jul 1 - Mar 31
	1c. Assimilate and regionalize net-load and stremflow data	Jul 1 - Mar 31
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		
DOE	**Cost-share**	**Total**
$872.3K	$218.1K	$1090.4K

FY20	FY21	Total Actual Costs FY20–FY21
Costed	**Costed**	**Total Costed**
$169.4K	$335.4K	$504.8K



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.

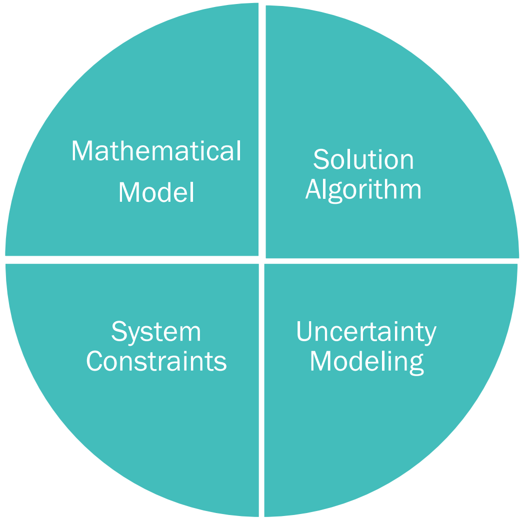
U.S. Army Corps of Engineers (USACE), Engineer Research and Development Center (ERDC) Costal and Hydraulic Laboratory has *endorsed* and *supports* this project.

- ✓ 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.

Performance: Accomplishments and Progress

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

Reservoir	Installed Capacity (MW)	Annual Generation (GWh)
Fort Peck	185.0	1,048
Garrison	583.3	2,250
Oahe	786.0	2,621
Big Bend	494.0	969
Fort Randal	320.0	1,727
Gavins Point	132.0	727
Total	2,500.3	9,342

Figure 3: Map and the geolocation of the case-study

Performance: Accomplishments and Progress

- 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.

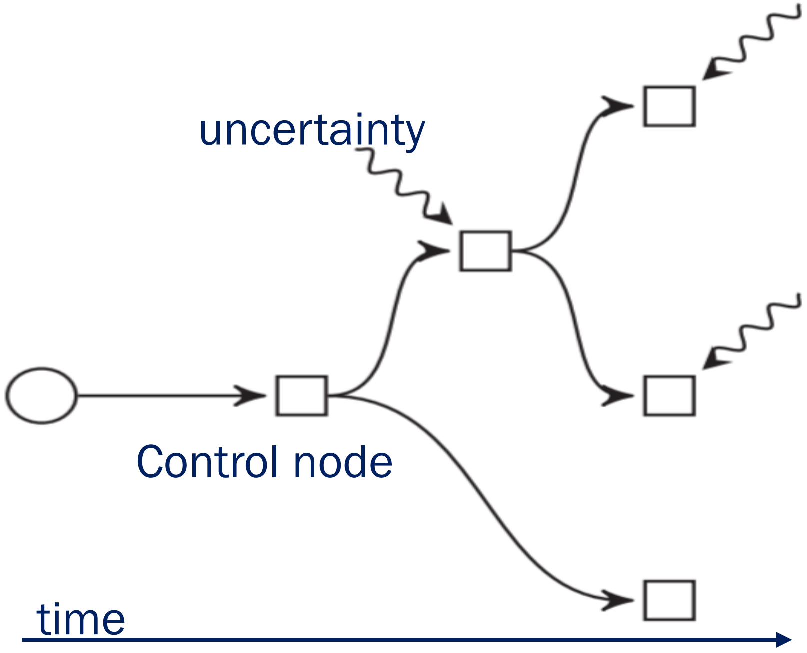


Figure 4. Schematic of decision nodes on a policy graph

Operational

- Storage balance equation
- Release
- Energy production equation
- Demand fulfillment
- Discharge capacity
- Generation capacity
- Storage capacity
- Spill capacity

Regulatory

- Rate of Change in Release
  $|release\text{out} - release\text{in}| \leq M$

Environmental

- Water quality
- Fish and Wildlife
- Threatened and Endangered Specie

Figure 5. Missouri River Basin system constraints

Performance: Accomplishments and Progress

- 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 <u>*policy*</u>.

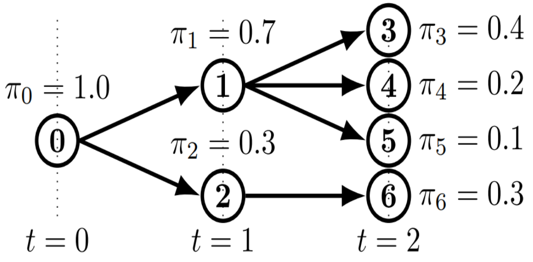


Figure 6. A scenario tree starting from a known state at root node $t = 0$ i.e., present state and splitting off at $t = 1$ and $t = 2$ to account for multiple possible futures.

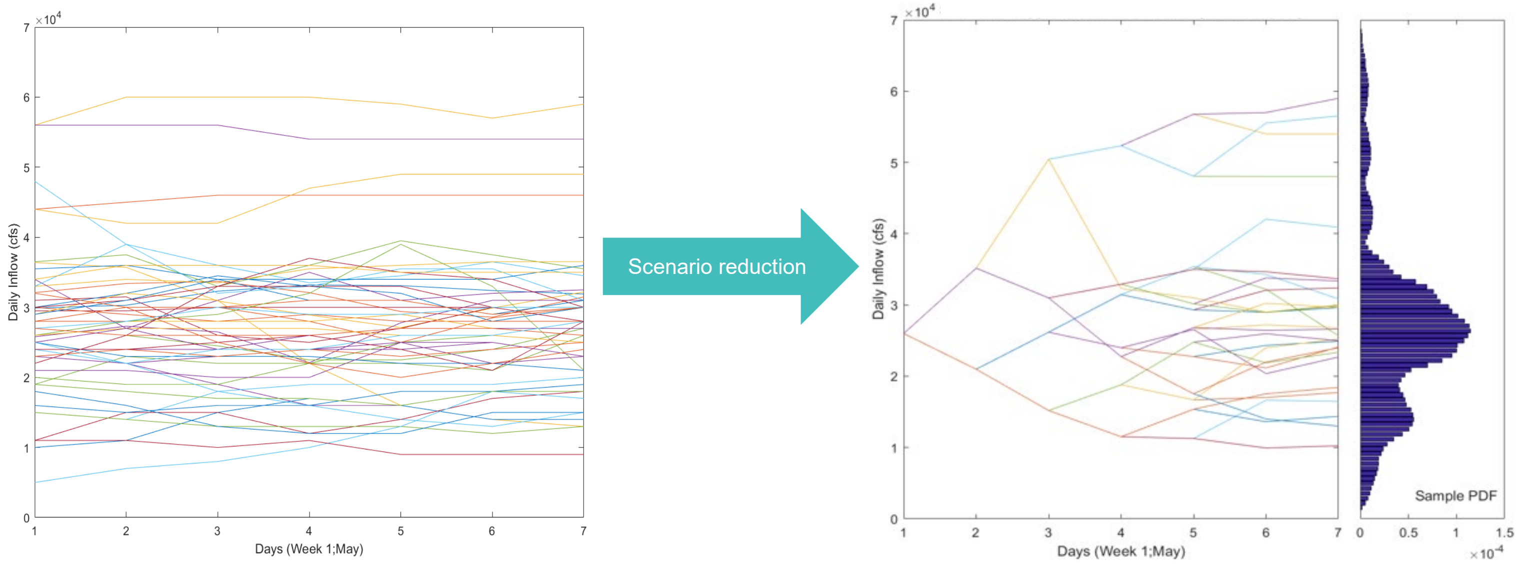


Figure 7: (left) Historical daily streamflow trajectories for first week of May. (right) Corresponding scenario tree with branching structure [1 2 2 2 2 2 1]

Performance: Accomplishments and Progress

- 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.

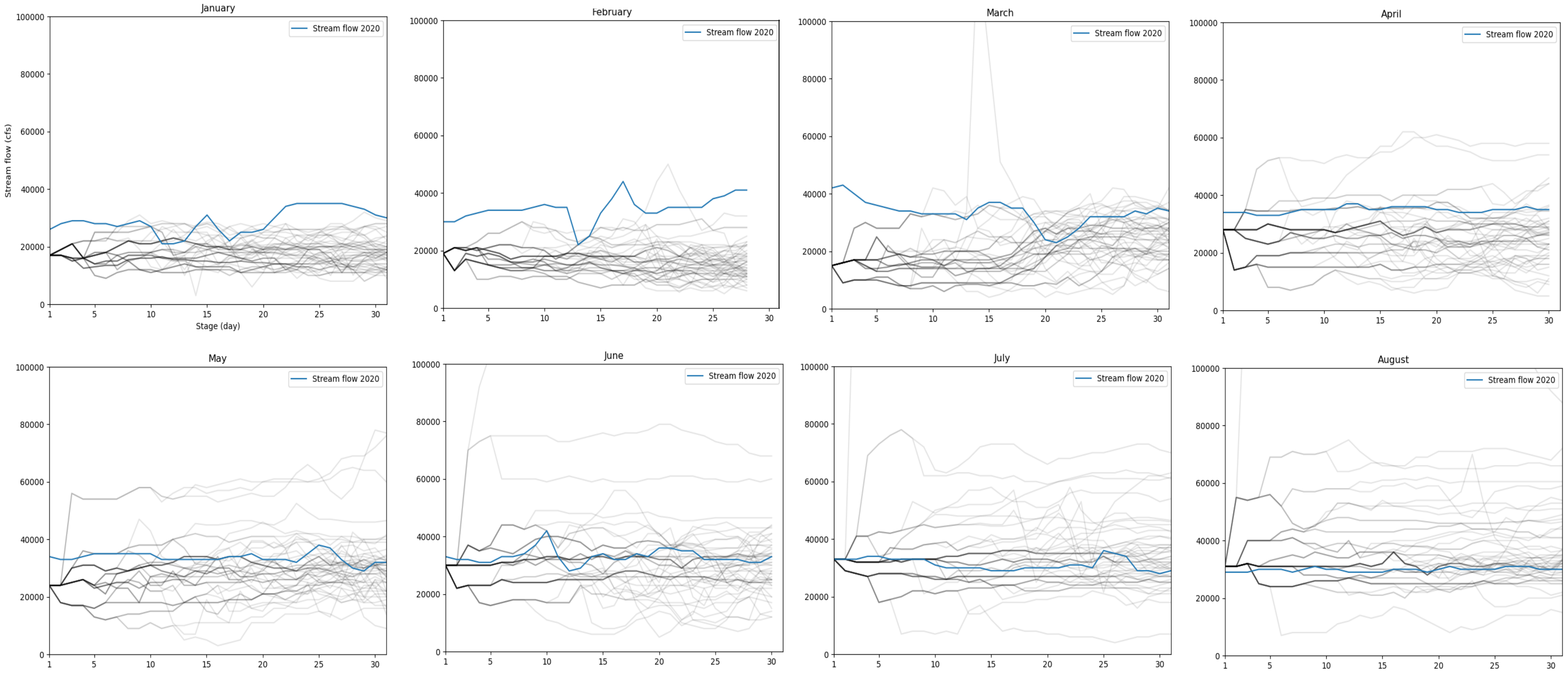


Figure 8: Monthly streamflow scenario trees for Gavins Point

Performance: Accomplishments and Progress

- 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.

FACILITY

Optimal solution space for releases under existing **O**perational, **E**nvironmental, **R**egulatory constraints.

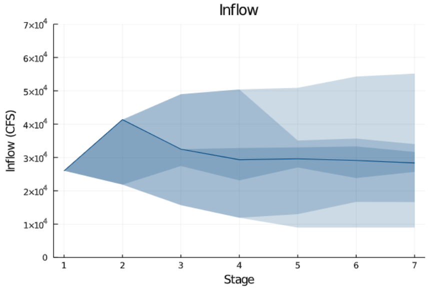
Modeled uncertainty + System constraints (O, E, R)

SDDP Algorithm

WATER SYSTEM

- Inflow scenario trees (to capture the uncertainty)
- Approximation error is minimized

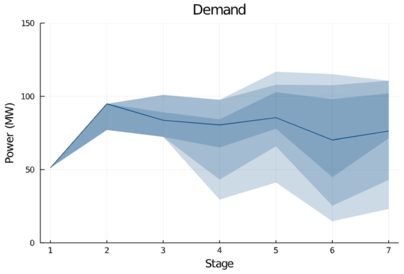
Scenario Reduction

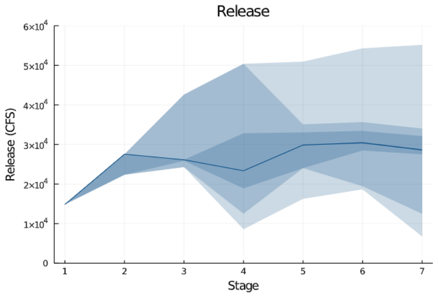


POWER SYSTEM

- Net-load scenario trees (to capture the uncertainty)
- Approximation error is minimized

Scenario Reduction

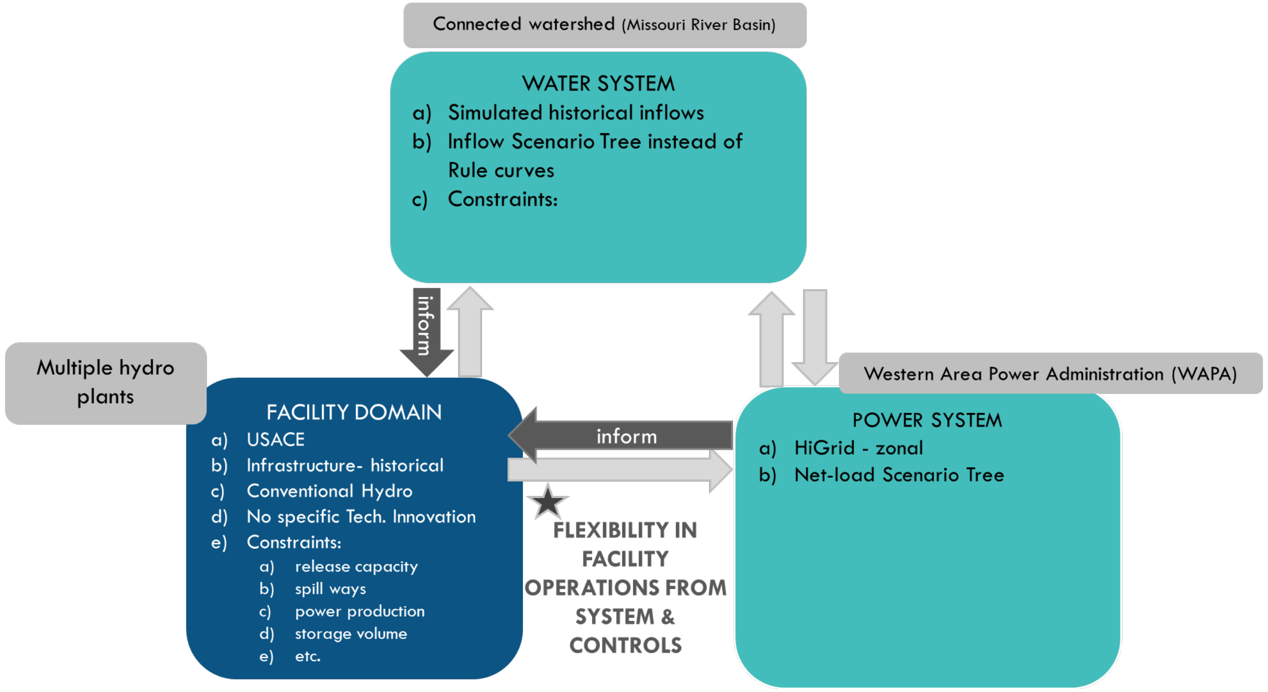




The methodology can find a flexible range of operational scenarios for each decision variable.

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.



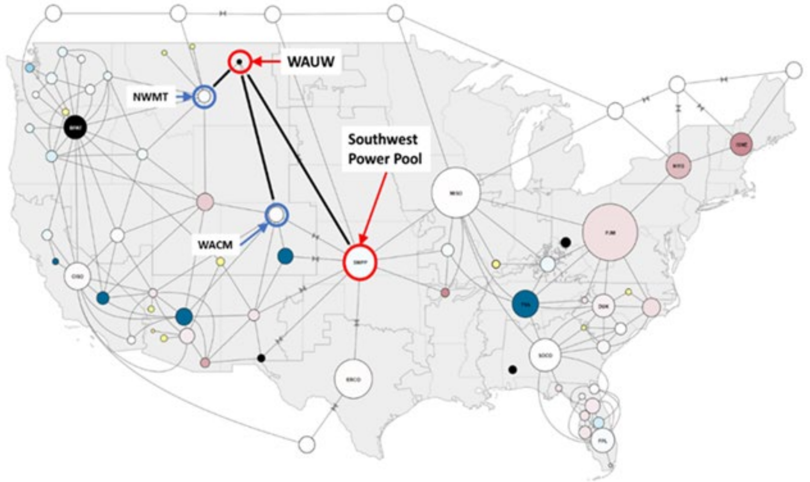
Flexibility: Measurable function of joint inflow and net-load distribution.

$$\mathrm{f}: \mathrm{X} \rightarrow \mathrm{Y}$$
$$\forall\ \mathrm{R} \in \sigma(\mathrm{Y}), \exists\ pre-image\ in\ \sigma(\mathrm{X})$$
$$\mathrm{f}^{-1}(\mathrm{R}) \coloneqq \{\mathrm{x} \in \mathrm{X}: \mathrm{f}(\mathrm{x}) \in \mathrm{R}\}$$

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.

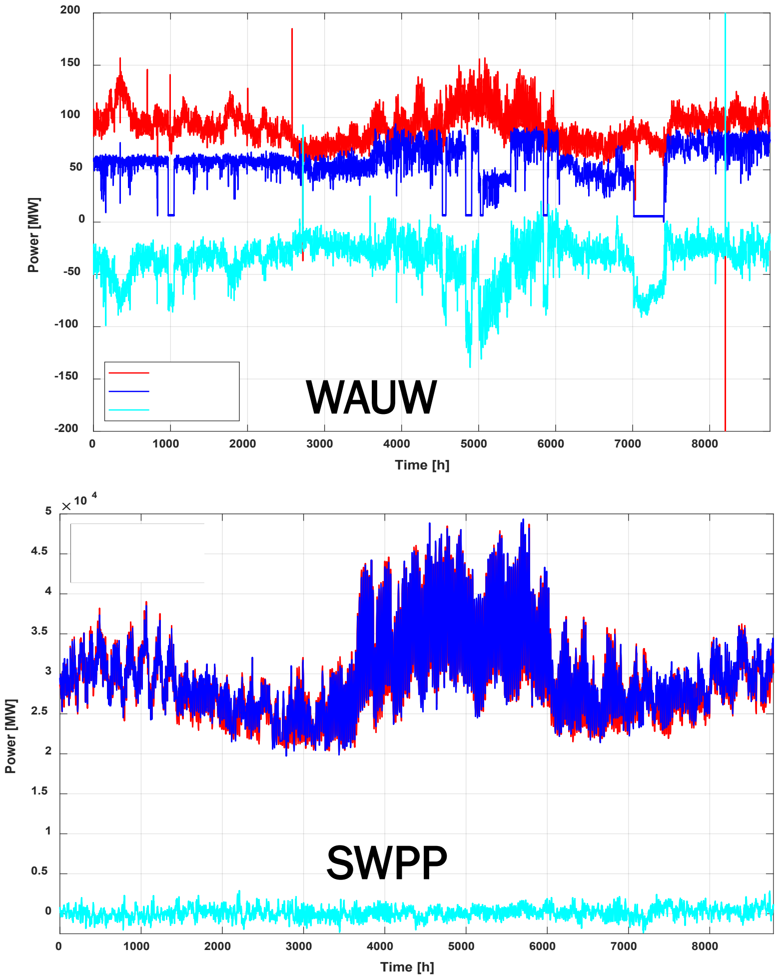


Figure 9: Hourly power generation portfolio

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.

Q&A