Boosting Power System Operation Economics via Closed-Loop Predict-and-Optimize

Ph.D. Thesis Defense

Ph.D. Candidate: Xianbang Chen

Advisor: Professor Lei Wu

STEVENS INSTITUTE OF TECHNOLOGY 1870

December 04, 2024

Advisory Committee

Professor Lei Wu (Chairman)

Department of Electrical and Computer Engineering

Professor Philip Odonkor

Department of Systems and Enterprises

Professor Shirantha Welikala

Department of Electrical and Computer Engineering

Professor Hao Wang

Department of Electrical and Computer Engineering

Boosting Power System Operation Economics via Closed-Loop Predict-and-Optimize

Ph.D. Thesis Defense

Ph.D. Candidate: Xianbang Chen

Advisor: Professor Lei Wu

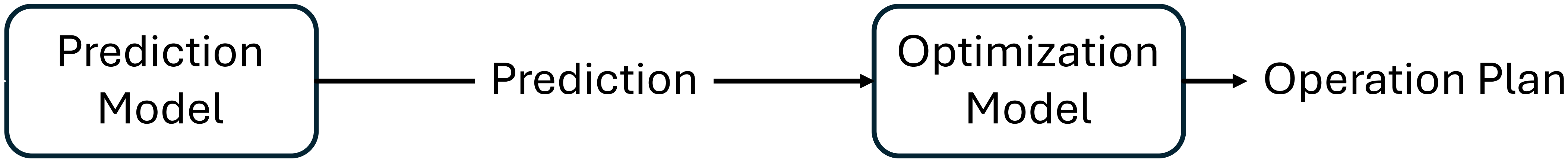
December 04, 2024

Content

1. Background
2. Proposal Recap
3. An Uncertainty-Aware Mid-Term Planning for Cascaded Hydropower
4. A DRL-Based Mid-Term Planning for Renewable-Integrated Cascaded Hydropower
5. Summary

Background: Power System Operation

- **Open-loop predict-then-optimize (OPO) process**



Use machine learning models, e.g., neural networks [1].

Solve operation models, e.g., mixed-integer linear programming (MILP) [2].

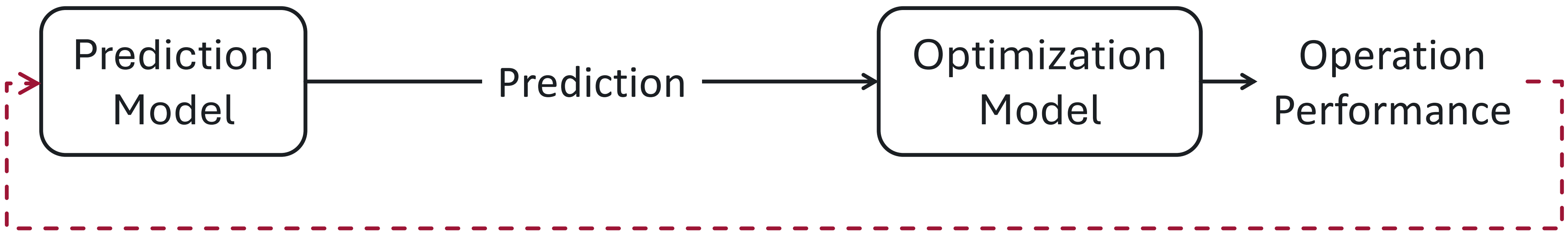
- **Operation goal**

  Minimum operation cost or maximum operation revenue, i.e., optimal operation economics.

[1]. S. Fang and H. -D. Chiang, "A High-Accuracy Wind Power Forecasting Model," in *IEEE Transactions on Power Systems*, 2017.
[2]. L. Wu, M. Shahidehpour and T. Li, "Stochastic Security-Constrained Unit Commitment," in *IEEE Transactions on Power Systems*, 2007.

Background: Open-Loop Idea vs Closed-Loop Idea

We challenge the traditional OPO framework:



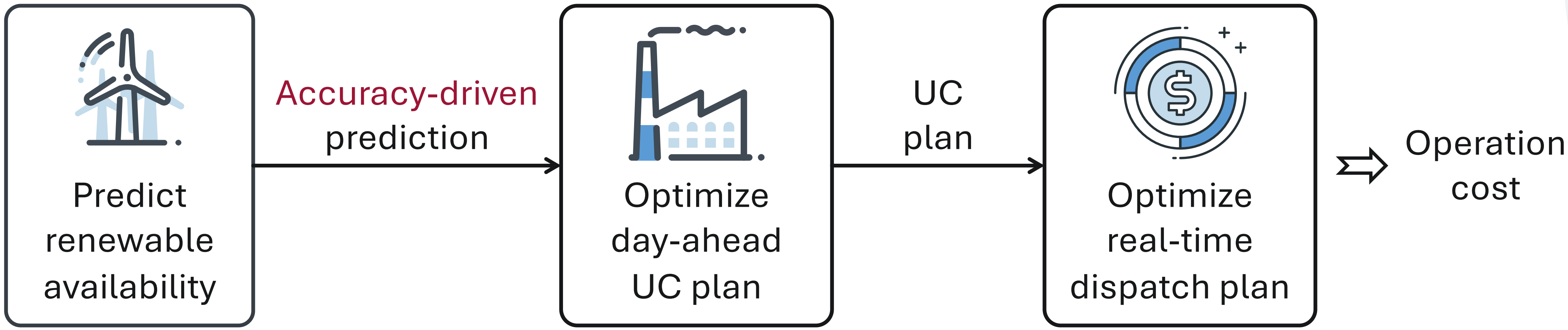
Closed-loop predict-and-optimize[3, 4] (CPO) idea:
To improve operation performance, the prediction model should consider its impact on the operation performance.

[3]. A. N. Elmachtoub, P. Grigas, "Smart “Predict, then Optimize”," in *Management Science*, 2022.
[4]. G. Y. Ban, C. Rudin, "The Big Data Newsvendor: Practical Insights from Machine Learning," in *Operations Research*, 2018.

Content

Proposal Recap

- **Operation problem: Unit commitment (UC) in OPO**



Use machine learning models to predict available renewable power in next day.

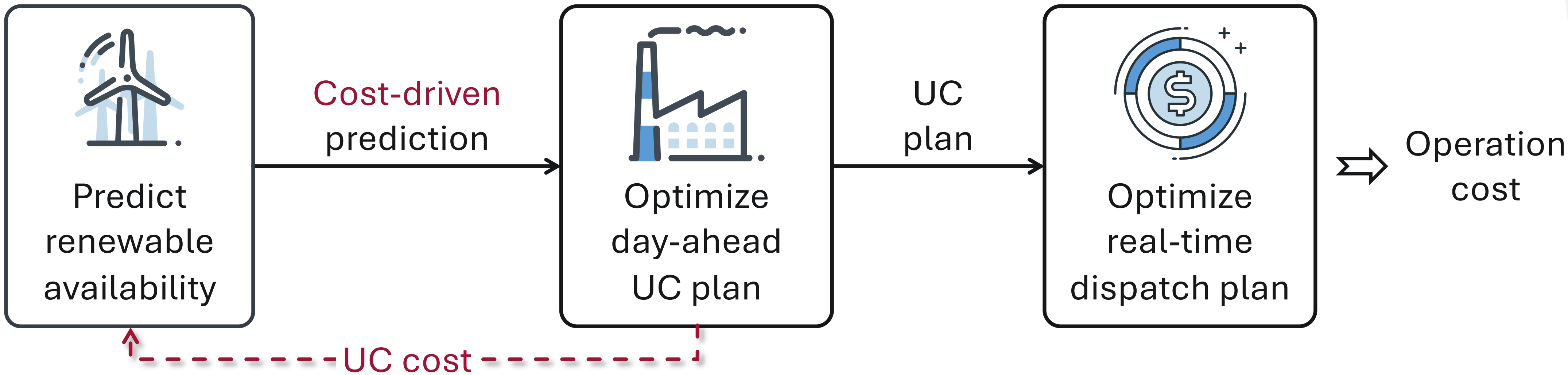
Solve a MILP model to determine the optimal UC plan, i.e., ON/OFF state and generation of units.

Solve MILP models to determine the optimal real-time dispatch plan.

- **Proposal goal: Reduce operation cost**
- **Research gap: Few CPO methods for MILP problems**

Proposal Recap

- **Training cost-driven prediction model for UC**

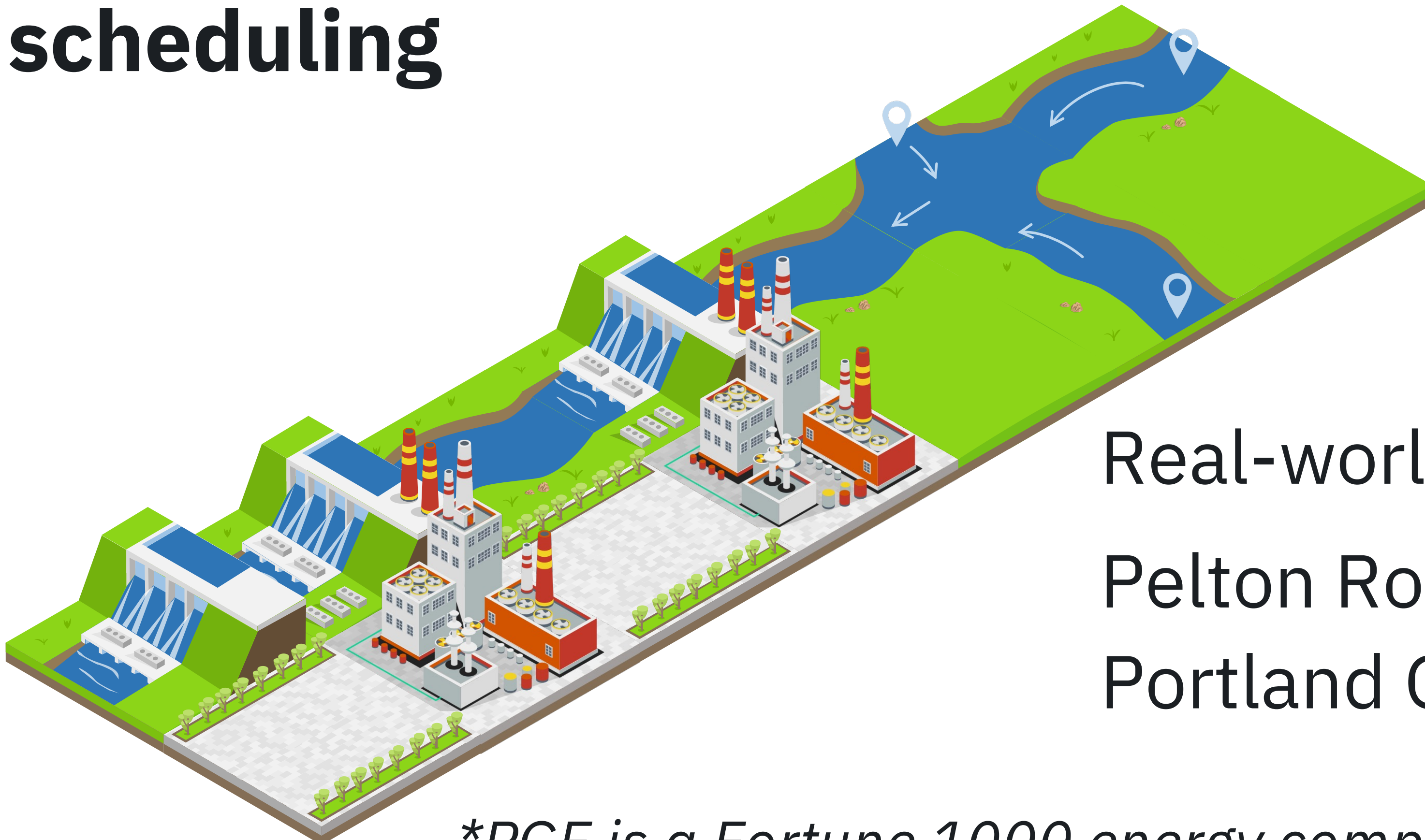


- **Key methodologies**

  1) Empirical risk minimization and bilevel programming
  2) Lagrangian decomposition and parallel computing

Subsequent Research

- **Engineering problem: Cascaded hydropower (CHP) scheduling**



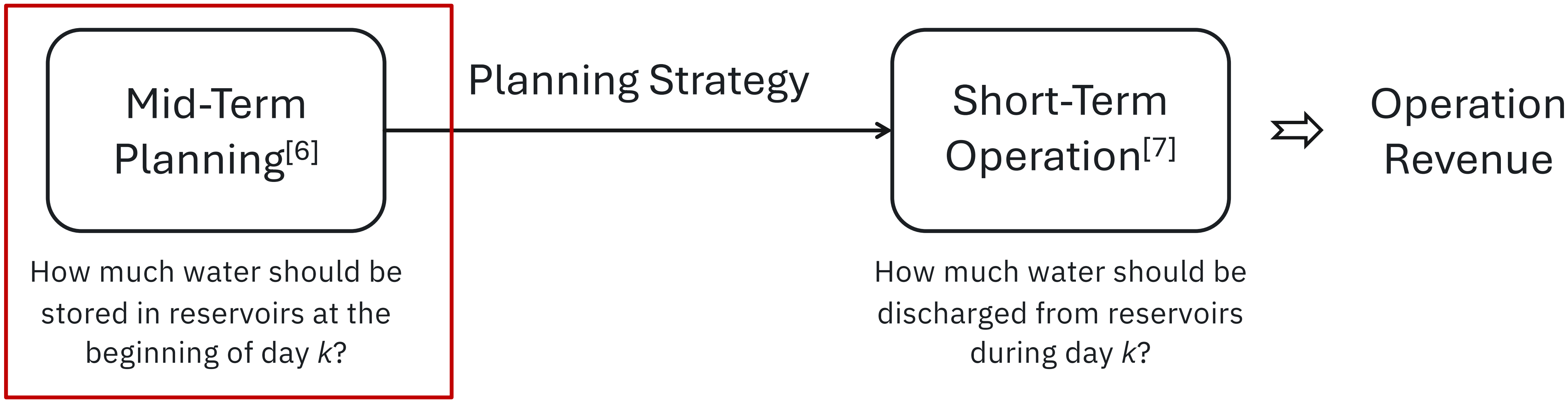
Real-world case:

Pelton Round Butte System of Portland General Electric (PGE)

**PGE is a Fortune 1000 energy company in Portland, OR*

Subsequent Research

- **Open-loop relationship between mid-term planning and short-term operations**



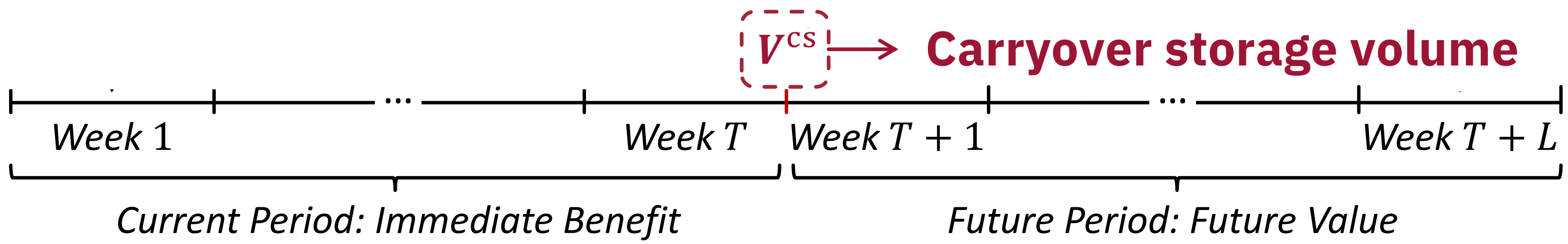
- **Research goal: Assist PGE in improving revenue**

[6]. A. Helseth, M. Fodstad and B. Mo, "Optimal Medium-Term Hydropower Scheduling Considering Energy and Reserve Capacity Markets," in *IEEE Transactions on Sustainable Energy*, 2016.
[7]. A. Helseth, S. Jaehnert and A. L. Diniz, "Convex Relaxations of the Short-Term Hydrothermal Scheduling Problem," in *IEEE Transactions on Power Systems*, 2021.

Content

An Uncertainty-Aware Mid-Term Planning for Cascaded Hydropower

- **What is mid-term hydropower planning?**



$$\max_{\boldsymbol{V}^{cs},\Xi} \overbrace{A(\boldsymbol{V}^{cs},\Xi,\hat{\boldsymbol{W}}^{cp})}^{\text{Immediate Benefit}} + \overbrace{F(\boldsymbol{V}^{cs},\hat{\boldsymbol{W}}^{fp})}^{\text{Future Value}}$$

$$\text{s.t.} \quad \boldsymbol{V}^{cs},\Xi \in \mathcal{X}(\hat{\boldsymbol{W}}^{cp});$$

Water inflow predictions ($\hat{\boldsymbol{W}}^{cp}$, $\hat{\boldsymbol{W}}^{fp}$)

Operation constraints (E.g., storage limits) ($\mathcal{X}(\hat{\boldsymbol{W}}^{cp})$)

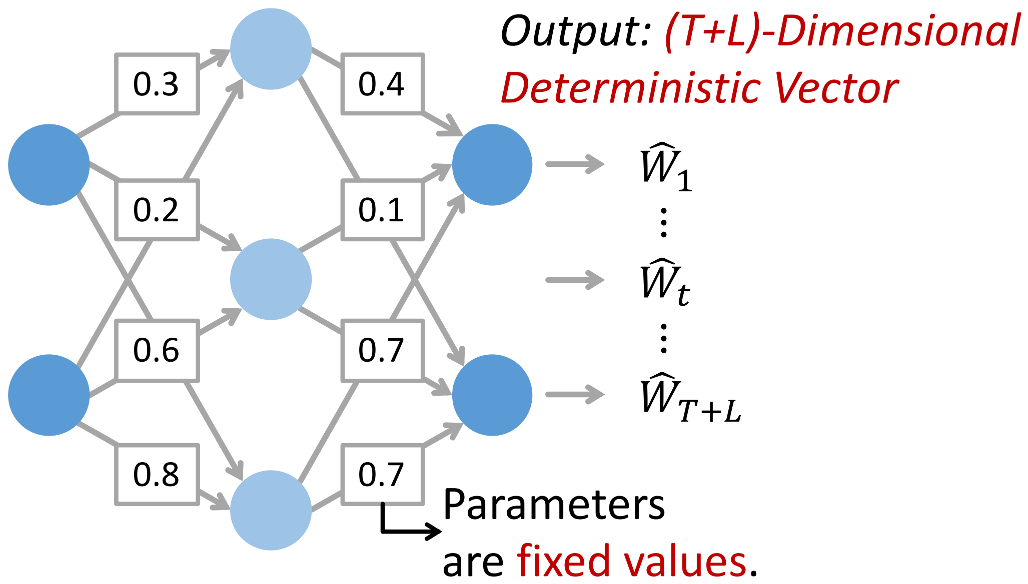
Remaining decisions (E.g., discharging) (Ξ)

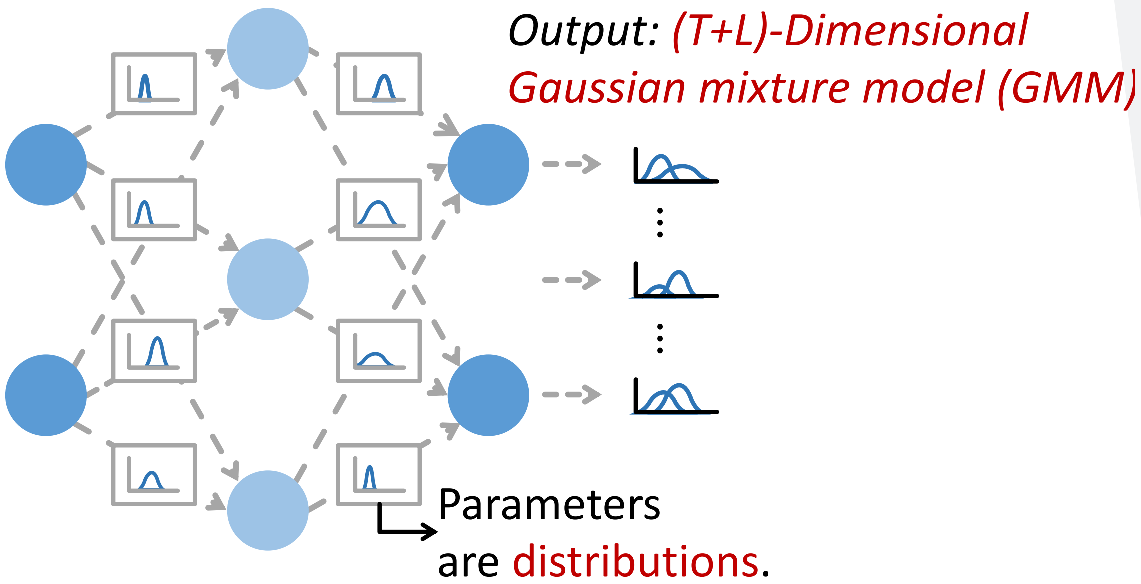
An Uncertainty-Aware Mid-Term Planning for Cascaded Hydropower

- **Questions to be addressed**
  1) How to predict water inflow and capture uncertainties associated with these predictions?

An Uncertainty-Aware Mid-Term Planning for Cascaded Hydropower

- **Bayesian neural network (BNN) for WI predictions**





Deep neural network: Cannot capture uncertainty.

Bayesian neural network: Can capture uncertainties, i.e., uncertainty-aware.

An Uncertainty-Aware Mid-Term Planning for Cascaded Hydropower

- **Mid-term planning model with GMM-based WI predictions**

$$\max_{\Xi, \boldsymbol{V}^{\text{cs}}} \overbrace{\sum_{n\in\mathcal{N}} \sum_{i\in\mathcal{I}_n} \sum_{t\in\mathcal{T}} \lambda P^{\diamond}_{nit}}^{\text{Immediate Benefit}} + \overbrace{F(\boldsymbol{V}^{\text{cs}})}^{\text{Future Value}}$$

$$\text{where } \Xi = \{D^{\diamond}_{nit}, I^{\diamond}_{nit}, P^{\diamond}_{nit}, S^{\diamond}_{nt}, V^{\diamond}_{n}, W^{\Delta}_{nt}, Z_r\}$$

$$\text{s.t. } \mathbb{P}\left\{ \begin{array}{l} V^{\diamond}_{n,1} + \sum_{\tau=1}^{t} (\hat{W}^{\text{cp}}_{n\tau} + W^{\Delta}_{n\tau}) \le V^{\text{M}}_{n}, \forall n; \\ V^{\diamond}_{n,1} + \sum_{\tau=1}^{t} (\hat{W}^{\text{cp}}_{n\tau} + W^{\Delta}_{n\tau}) \ge V^{\text{m}}_{n}, \forall n; \end{array} \right\} \ge 1 - \epsilon_t, \qquad \forall t;$$

$$W^{\Delta}_{nt} = \sum_{m\in\bar{\mathcal{N}}_n} (\sum_{i\in\mathcal{I}_m} \alpha D^{\diamond}_{m,i,t-\delta} + S^{\diamond}_{m,t-\delta}) - \sum_{i\in\mathcal{I}_n} \alpha D^{\diamond}_{nit} - S^{\diamond}_{nt},\ S^{\diamond}_{nt} \ge 0, \qquad \forall n, \forall t;$$

$$V^{\diamond}_{n,t+1} = V^{\diamond}_{n,1} + \sum_{\tau=1}^{t} (\hat{W}^{\text{cp},\mu}_{n\tau} + W^{\Delta}_{n\tau}), \qquad \forall n, \forall t;$$

$$V^{\text{m}}_{n} \le V^{\diamond}_{nt} \le V^{\text{M}}_{n}, \qquad \forall n, \forall t;$$

$$V^{\text{cs}}_{n} = V^{\diamond}_{n,T+1}, \qquad \forall n;$$

$$P^{\diamond}_{nit} = \mathcal{P}^{\text{RtP}}(D^{\diamond}_{nit}, I^{\diamond}_{nit}), I^{\diamond}_{nit} \in \{0,1\}, \qquad \forall n, \forall i, \forall t;$$

$$P^{\text{m}}_{ni} I_{nit} \le P^{\diamond}_{nit} \le P^{\text{M}}_{ni} I_{nit},\ D^{\text{m}}_{ni} I_{nit} \le D^{\diamond}_{nit} \le D^{\text{M}}_{ni} I_{nit}, \qquad \forall n, \forall i, \forall t;$$

Joint chance constraint
(Under uncertain WI, the probability of satisfying the storage limit is at least $1 - \epsilon_t$)

By Boole's inequality

By affine invariance of GMM

By Newton method

↓

Deterministic linear constraints

An Uncertainty-Aware Mid-Term Planning for Cascaded Hydropower

- **Questions to be addressed**

  1) How to quantify the future value in an easy-to-understand and easy-to-use way?

An Uncertainty-Aware Mid-Term Planning for Cascaded Hydropower

- **Quantifying model of future value**

$$\max_{\Psi} \sum_{n\in\mathcal{N}} \sum_{i\in\mathcal{I}_n} \lambda L_n^{\text{dis}} P_{ni} - \sum_{n\in\mathcal{N}} C_n^{\text{ws}} S_n$$

$$\text{where } \Psi = \{\boldsymbol{L}^{\text{n-dis/dis}}, \boldsymbol{L}^{\Delta}, \boldsymbol{D}, \boldsymbol{S}, \boldsymbol{P}, \boldsymbol{I}, \boldsymbol{W}^{\Delta/\text{i/o}}\}$$

$$\text{s.t. } L_n^{\text{n-dis}} + L_n^{\text{dis}} = L,\ L_n^{\text{n-dis}} \ge 0,\ L_n^{\text{dis}} \ge 0, \quad \forall n;$$

$$\begin{cases} V_n^{\text{m}} \le V_n^{\text{cs},\theta} + \frac{L_v^{\text{n-dis}} \hat{W}_n^{\text{fp}}}{L} + W_{vn}^{\text{i}} - W_{vn}^{\text{o}} \le V_n^{\text{M}}, \forall v \in \{n, \bar{\mathcal{N}}_n\}; \\ W_{vn}^{\text{i}} = \sum_{m\in\bar{\mathcal{N}}_n} (\alpha L_{vm}^{\Delta} \sum_{i\in\mathcal{I}_m} D_{mi}), \quad \forall v \in \{n, \bar{\mathcal{N}}_n\}; \\ W_{vn}^{\text{o}} = \alpha L_{vn}^{\Delta} \sum_{i\in\mathcal{I}_n} D_{ni}, \quad \forall v \in \{n, \bar{\mathcal{N}}_n\}; \\ L_{vu}^{\Delta} = \max\{0, L_v^{\text{n-dis}} - L_u^{\text{n-dis}}\}, \quad \forall v, u \in \{n, \bar{\mathcal{N}}_n\}; \end{cases}, \quad \forall n;$$

$$V_n^{\text{m}} \le V_n^{\text{cs},\theta} + \hat{W}_n^{\text{fp}} + W_n^{\Delta} + \sum_{m\in\bar{\mathcal{N}}_n} S_m - S_n, \quad \forall n;$$

$$V_n^{\text{M}} \ge V_n^{\text{cs},\theta} + \hat{W}_n^{\text{fp}} + W_n^{\Delta} + \sum_{m\in\bar{\mathcal{N}}_n} S_m - S_n, \quad \forall n;$$

$$W_n^{\Delta} = \sum_{m\in\bar{\mathcal{N}}_n} (\alpha L_m^{\text{dis}} \sum_{i\in\mathcal{I}_m} D_{mi}) - \alpha L_n^{\text{dis}} \sum_{i\in\mathcal{I}_n} D_{ni},\ S_n \ge 0, \quad \forall n;$$

$$P_{ni} = \mathcal{P}^{\text{RtP}}(D_{ni}, I_{ni}),\ I_{ni} \in \{0,1\}, \quad \forall n, \forall i;$$

$$P_{ni}^{\text{m}} I_{ni} \le P_{ni} \le P_{ni}^{\text{M}} I_{ni},\ D_{ni}^{\text{m}} I_{ni} \le D_{ni} \le D_{ni}^{\text{M}} I_{ni}, \quad \forall n, \forall i;$$

⇒

$$\max_{\boldsymbol{x},\boldsymbol{y}} \ \boldsymbol{c}^\top \boldsymbol{x} + \boldsymbol{d}^\top \boldsymbol{y}$$

$$\text{s.t. } \boldsymbol{A}\boldsymbol{x} + \boldsymbol{E}\boldsymbol{y} \le \boldsymbol{b} + \boldsymbol{F}\boldsymbol{V}^{\text{cs},\theta};$$

$$\boldsymbol{x} \in \mathbb{R}_+^p,\ \boldsymbol{y} \in \{0,1\}^q;$$

→ Carryover storage is a parameter

Goal: Given a carryover storage volume, maximize revenue over the future period.

Idea: Derive water values.

Water values: Amount of revenue that a reservoir can generate with one incremental unit of stored water.

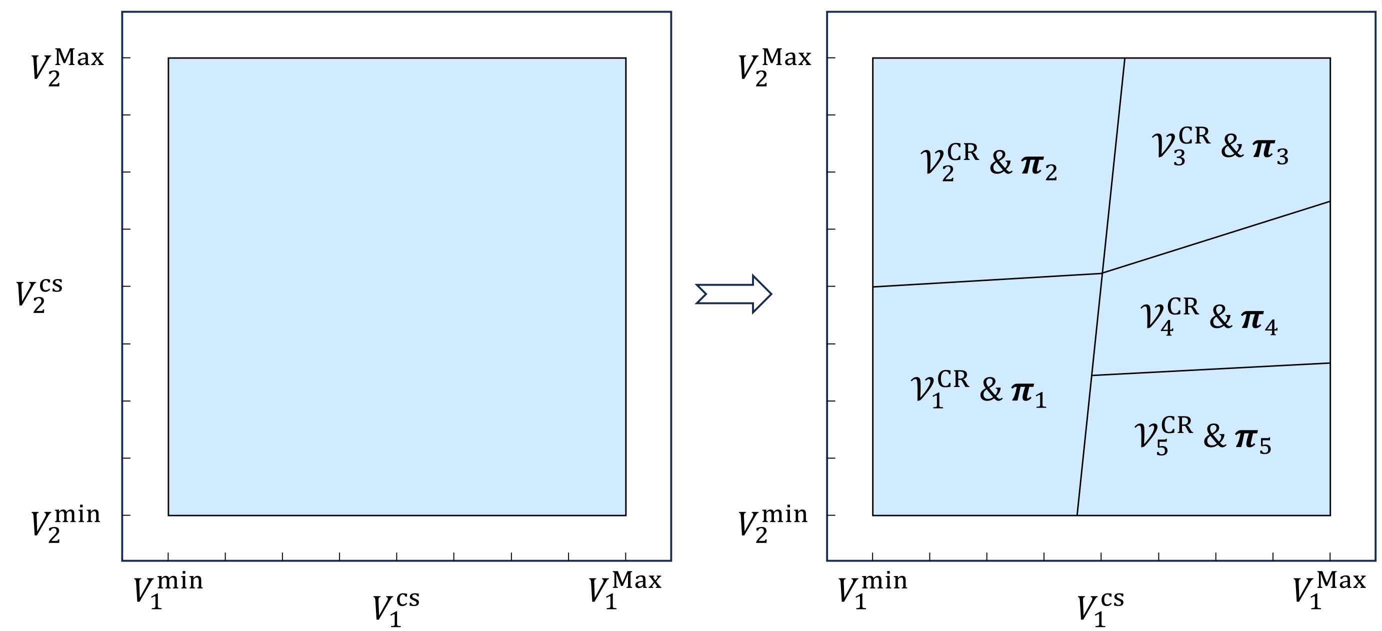
An Uncertainty-Aware Mid-Term Planning for Cascaded Hydropower

- **Get water values**

$$\max_{\boldsymbol{x},\boldsymbol{y}} \ \boldsymbol{c}^\top \boldsymbol{x} + \boldsymbol{d}^\top \boldsymbol{y}$$
$$\text{s.t.} \ \ \boldsymbol{A}\boldsymbol{x} + \boldsymbol{E}\boldsymbol{y} \leq \boldsymbol{b} + \boldsymbol{F}\boldsymbol{V}^{\mathrm{cs},\theta};$$
$$\boldsymbol{x} \in \mathbb{R}_+^p, \ \boldsymbol{y} \in \{0,1\}^q;$$

Use a partition-then-extract algorithm to calculate water values

A two-reservoir example



"If-then" rules

Deterministic linear constraints

$$F(\boldsymbol{V}^{\mathrm{cs}}) = \begin{cases} \pi_{1,1}(V_1^{\mathrm{cs}} - V_1^{\mathrm{min}}) + \pi_{1,2}(V_2^{\mathrm{cs}} - V_2^{\mathrm{min}}) & \text{if } \boldsymbol{V}^{\mathrm{cs}} \in \mathcal{V}_1^{\mathrm{CR}} \\ \pi_{2,1}(V_1^{\mathrm{cs}} - V_1^{\mathrm{min}}) + \pi_{2,2}(V_2^{\mathrm{cs}} - V_2^{\mathrm{min}}) & \text{if } \boldsymbol{V}^{\mathrm{cs}} \in \mathcal{V}_2^{\mathrm{CR}} \\ \pi_{3,1}(V_1^{\mathrm{cs}} - V_1^{\mathrm{min}}) + \pi_{3,2}(V_2^{\mathrm{cs}} - V_2^{\mathrm{min}}) & \text{if } \boldsymbol{V}^{\mathrm{cs}} \in \mathcal{V}_3^{\mathrm{CR}} \\ \pi_{4,1}(V_1^{\mathrm{cs}} - V_1^{\mathrm{min}}) + \pi_{4,2}(V_2^{\mathrm{cs}} - V_2^{\mathrm{min}}) & \text{if } \boldsymbol{V}^{\mathrm{cs}} \in \mathcal{V}_4^{\mathrm{CR}} \\ \pi_{5,1}(V_1^{\mathrm{cs}} - V_1^{\mathrm{min}}) + \pi_{5,2}(V_2^{\mathrm{cs}} - V_2^{\mathrm{min}}) & \text{if } \boldsymbol{V}^{\mathrm{cs}} \in \mathcal{V}_5^{\mathrm{CR}} \end{cases}$$

An Uncertainty-Aware Mid-Term Planning for Cascaded Hydropower (CHP)

- **Final mid-term CHP planning model**

$$\max_{\boldsymbol{V}^{\mathrm{cs}},\Xi} \overbrace{A(\boldsymbol{V}^{\mathrm{cs}},\Xi,\hat{\boldsymbol{W}}^{\mathrm{cp}})}^{\text{Immediate Benefit}} + \overbrace{F(\boldsymbol{V}^{\mathrm{cs}},\hat{\boldsymbol{W}}^{\mathrm{fp}})}^{\text{Future Value}}$$

$$\text{s.t. } \boldsymbol{V}^{\mathrm{cs}},\Xi \in \mathcal{X}(\hat{\boldsymbol{W}}^{\mathrm{cp}});$$

Future Value → "If-then" rules

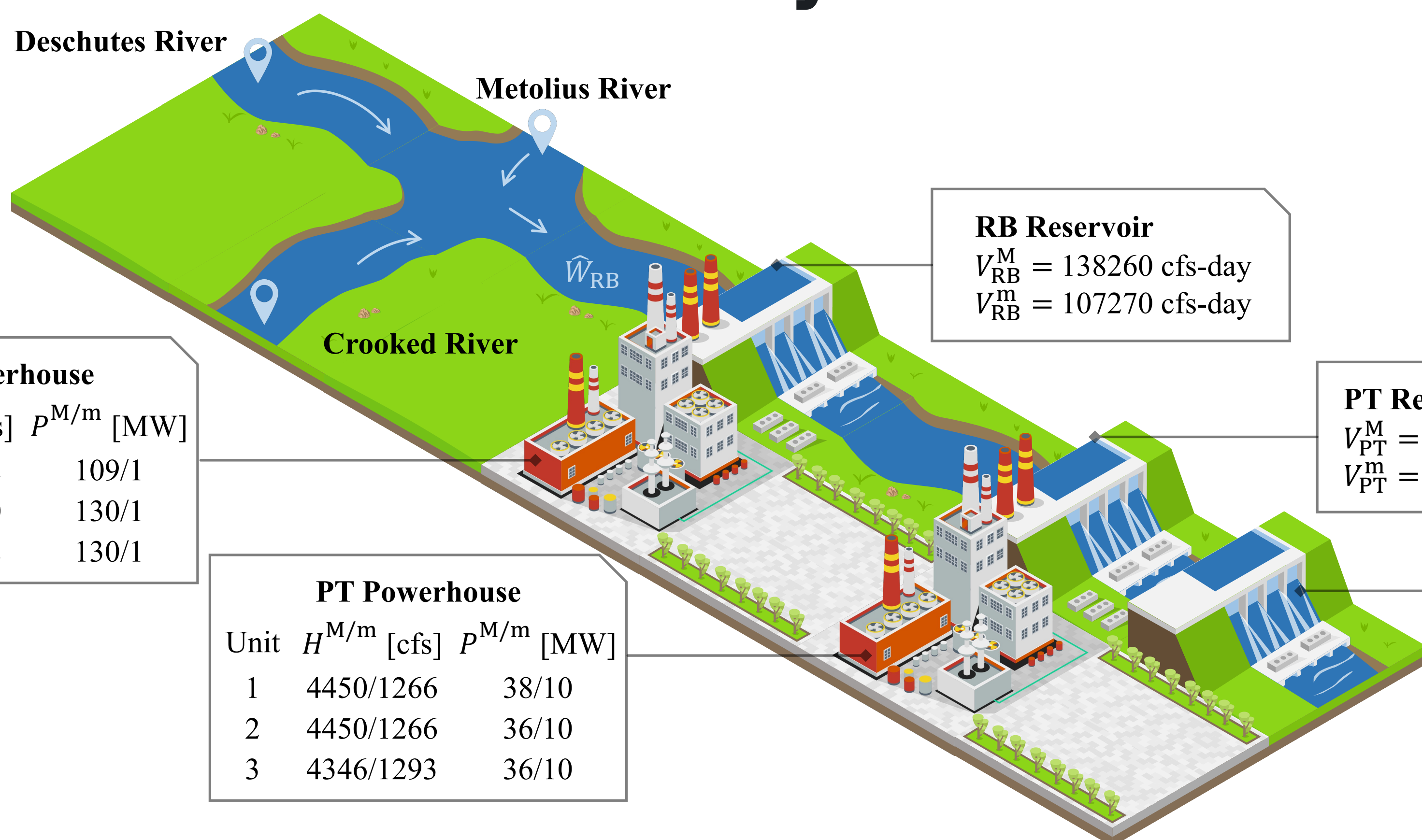
$\hat{\boldsymbol{W}}^{\mathrm{cp}}$, $\hat{\boldsymbol{W}}^{\mathrm{fp}}$ → BNN

$\boldsymbol{V}^{\mathrm{cs}},\Xi \in \mathcal{X}(\hat{\boldsymbol{W}}^{\mathrm{cp}})$ → Chance constraints

- **Mixed-integer linear programming**
- **Solving this model to determine optimal V^{cs}**

An Uncertainty-Aware Mid-Term Planning for Cascaded Hydropower

- **PGE's Pelton Round Butte System**



RB Powerhouse

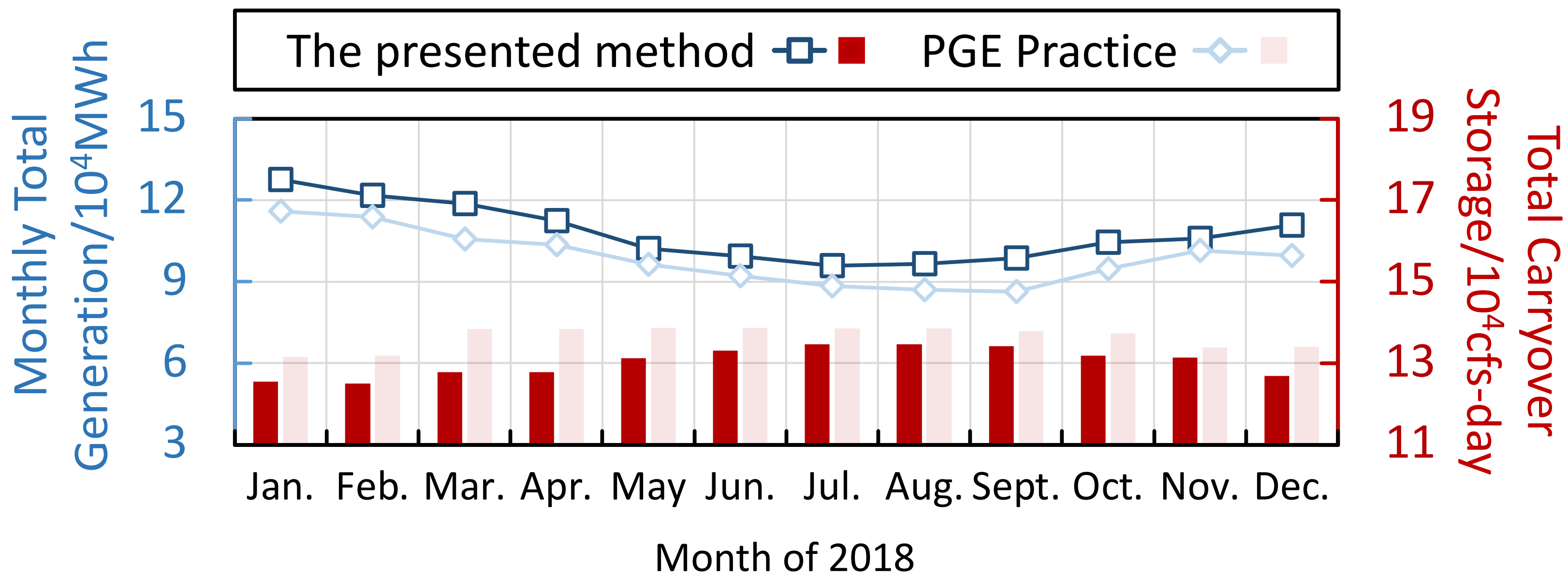
Unit	$H^{M/m}$ [cfs]	$P^{M/m}$ [MW]
1	5837/642	109/1
2	4604/340	130/1
3	5442/362	130/1

PT Powerhouse

Unit	$H^{M/m}$ [cfs]	$P^{M/m}$ [MW]
1	4450/1266	38/10
2	4450/1266	36/10
3	4346/1293	36/10

An Uncertainty-Aware Mid-Term Planning for Cascaded Hydropower

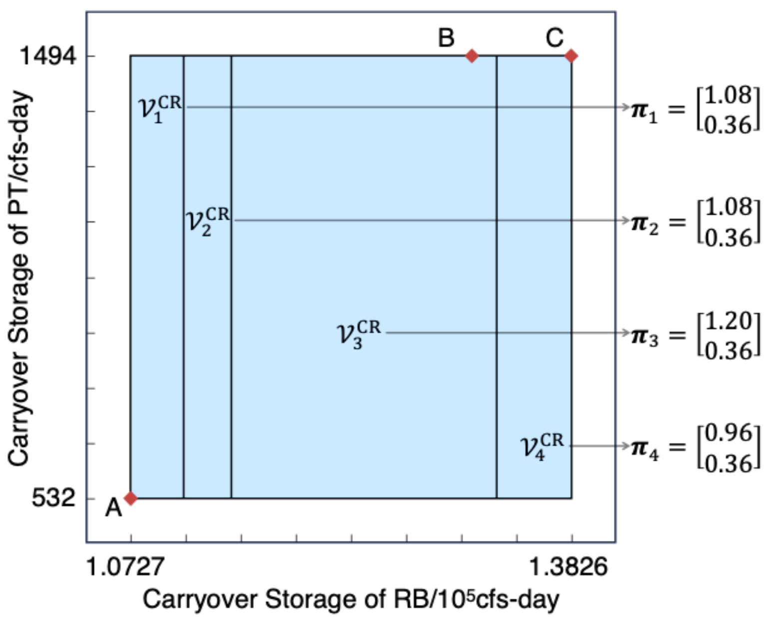
- **Main numerical results**

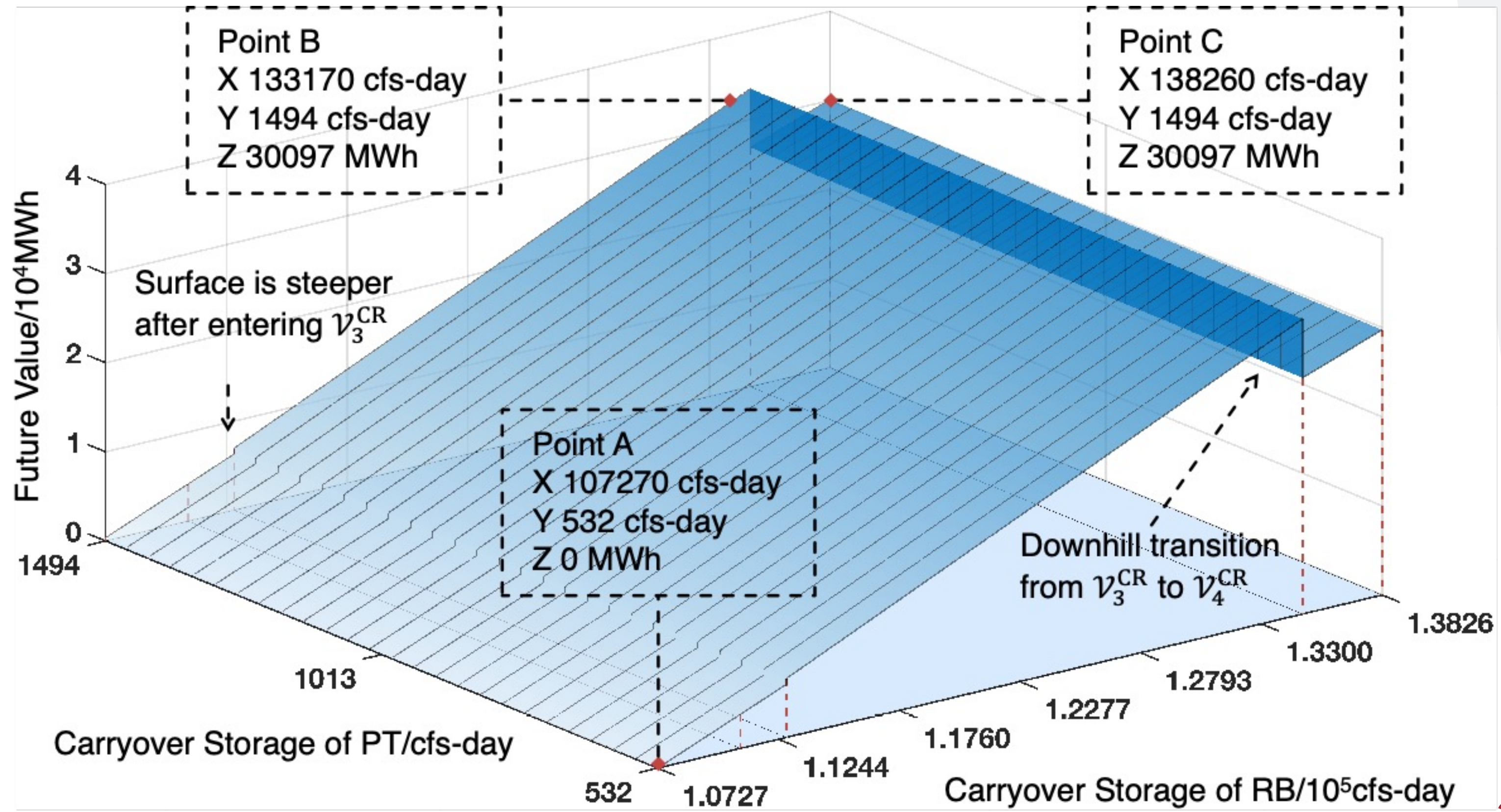


- The annual generation is 9.21% higher than PGE's practice.
- The carryover storage is slightly lower than PGE's practice. No violations of operation constraints.

An Uncertainty-Aware Mid-Term Planning for Cascaded Hydropower

- **Easy-to-understand "if-then" rules**





An Uncertainty-Aware Mid-Term Planning for Cascaded Hydropower

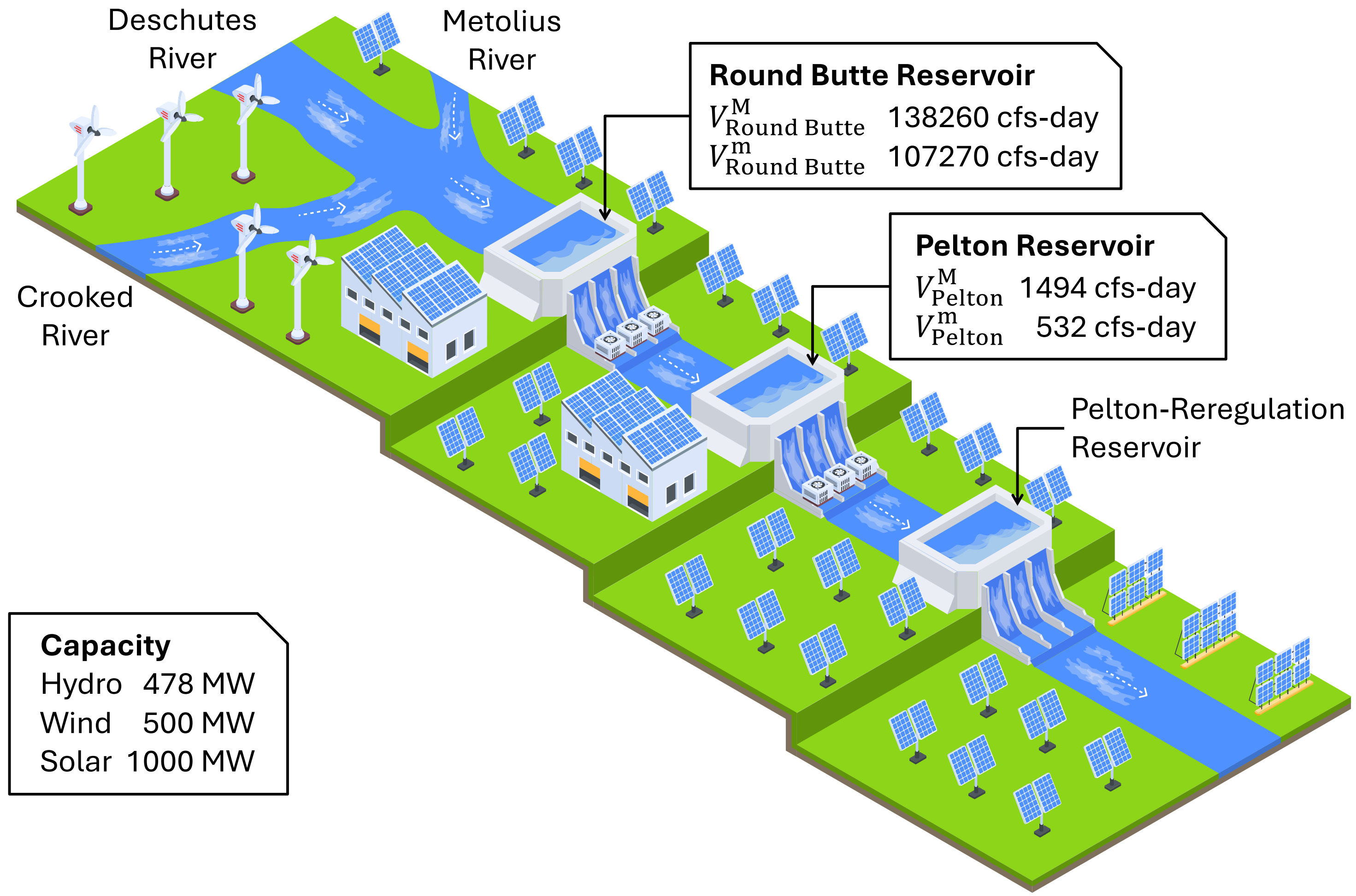
- **Summary**
  1) Target improving total generation by enhancing mid-term planning strategies
  2) BNN-based water inflow predictor
  3) Chance constraints for the current period
  4) “If-then” rules to quantify the future value
  5) Outperform PGE’s practice by 9.21%

Content

1. Background
2. Proposal Recap
3. An Uncertainty-Aware Mid-Term Planning for Cascaded Hydropower
4. A DRL-Based Mid-Term Planning for Renewable-Integrated Cascaded Hydropower
5. Summary

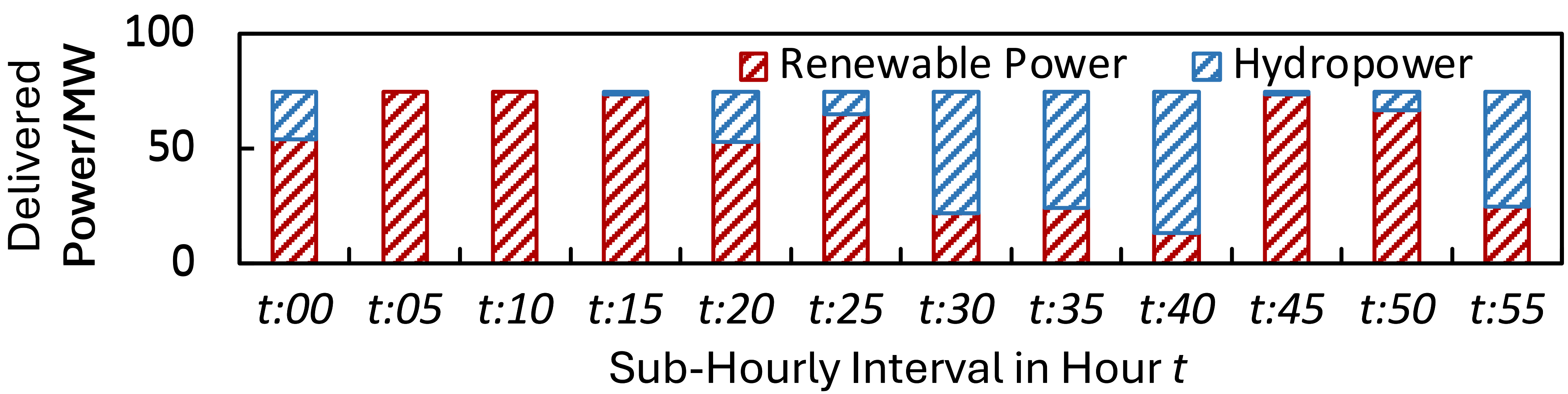
A DRL-Based Mid-Term Planning for Renewable-Integrated Cascaded Hydropower

- **PGE's Pelton Round Butte System with renewable integration**



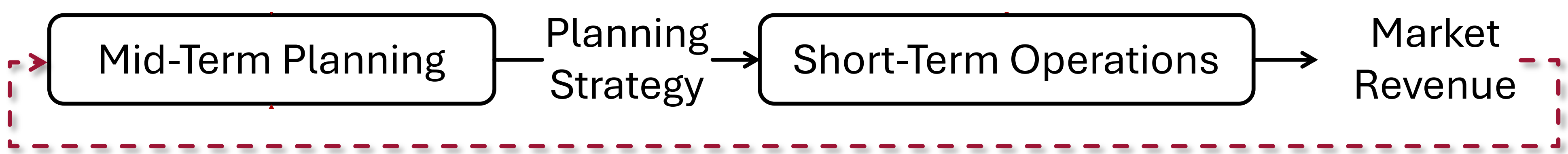
A DRL-Based Mid-Term Planning for Renewable-Integrated Cascaded Hydropower

- **Power-mix of renewable-integrated hydropower**



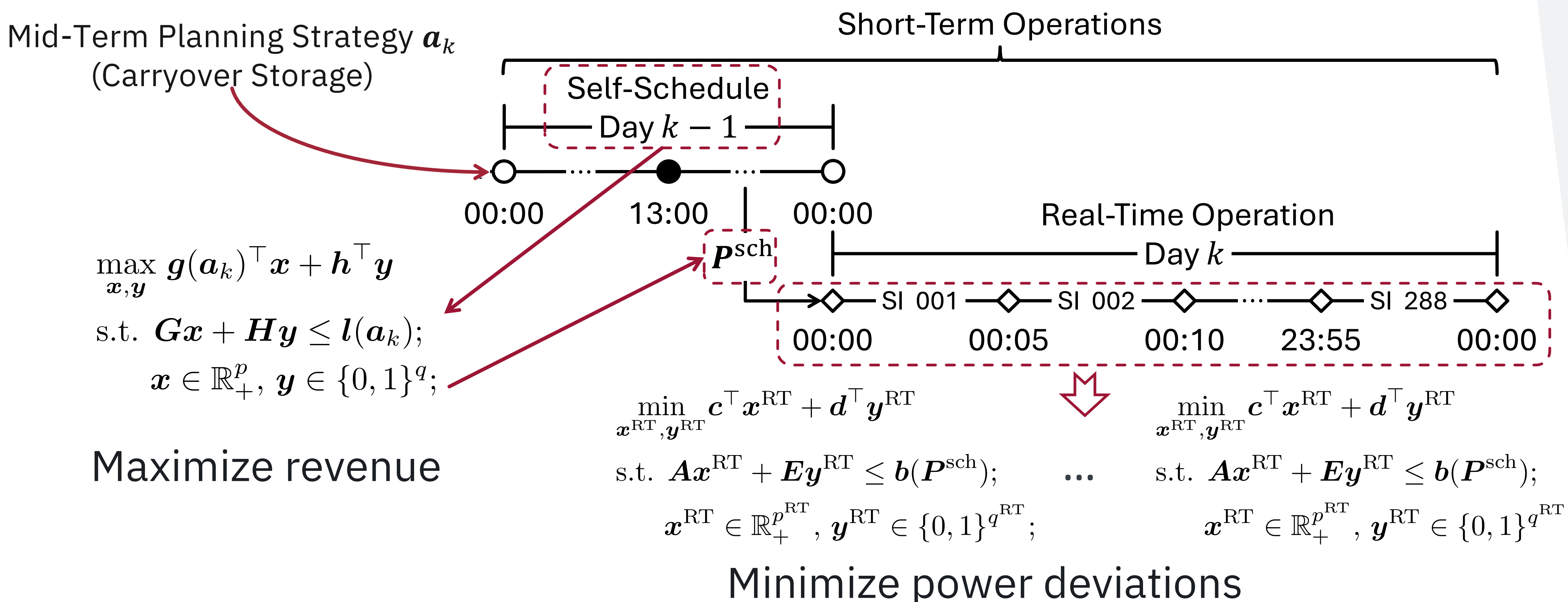
A DRL-Based Mid-Term Planning for Renewable-Integrated Cascaded Hydropower

- **Goal: Improve PGE's revenue in the context of renewable integration via CPO-based planning**



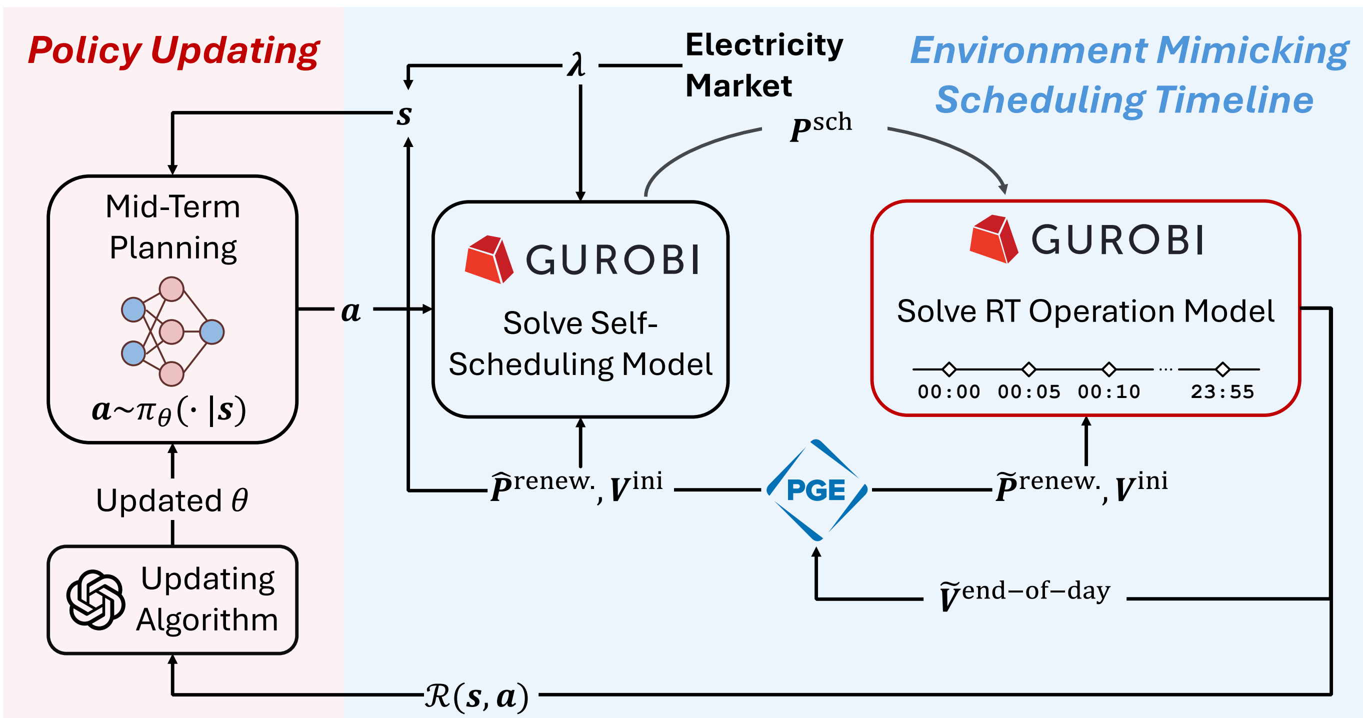
A DRL-Based Mid-Term Planning for Renewable-Integrated Cascaded Hydropower

- **From mid-term planning to short-term operations**



A DRL-Based Mid-Term Planning for Renewable-Integrated Cascaded Hydropower

- **Deep reinforcement learning-based framework**



a: Mid-term planning strategy

s: State vector

π_θ: Mid-term planning policy

$\mathcal{R}$: Reward (market revenue)

λ: Electricity price

$P^{renew.}$: Renewable power

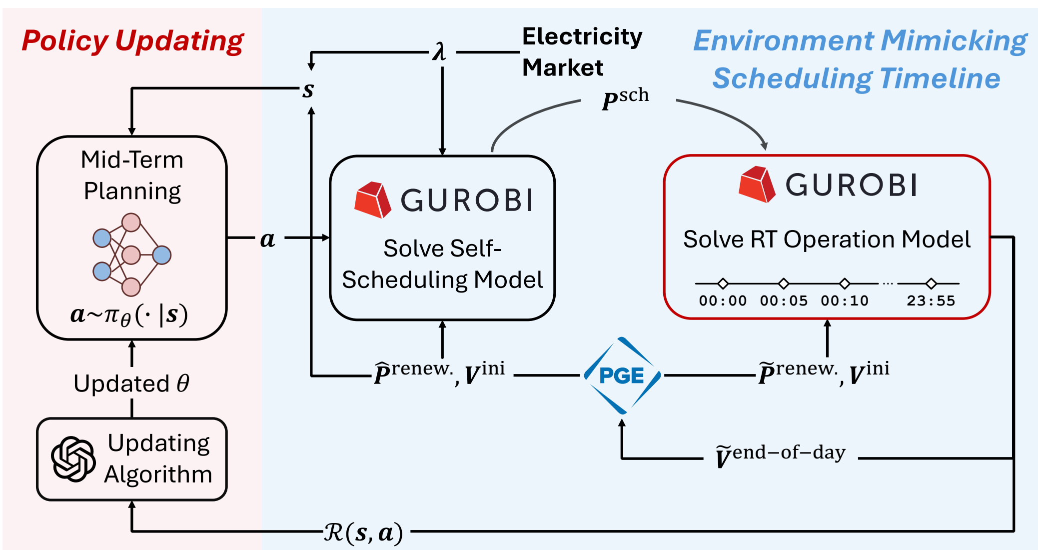
P^{sch}: Self-scheduling plan

V^{ini}: Initial storage

$\tilde{V}^{end-of-day}$: End-of-day storage

A DRL-Based Mid-Term Planning for Renewable-Integrated Cascaded Hydropower

- **Questions to be addressed**
  1) How to make the training process computationally affordable?



Each step solves 288 RT models

Each step takes about 3 minutes

Need 100,000+ training steps

A DRL-Based Mid-Term Planning for Renewable-Integrated Cascaded Hydropower

- **Training process accelerating via multi-parametric programming**

$$\begin{aligned} v^\star(\boldsymbol{\vartheta}) = & \min_{\boldsymbol{x}^{\mathrm{RT}}, \boldsymbol{y}^{\mathrm{RT}}} \ \boldsymbol{c}^\top \boldsymbol{x}^{\mathrm{RT}} + \boldsymbol{d}^\top \boldsymbol{y}^{\mathrm{RT}} \\ \text{s.t.} \ & \boldsymbol{A}\boldsymbol{x}^{\mathrm{RT}} + \boldsymbol{E}\boldsymbol{y}^{\mathrm{RT}} \leq \boldsymbol{F}\boldsymbol{\vartheta} + \boldsymbol{b}; \\ & \boldsymbol{x}^{\mathrm{RT}} \in \mathbb{R}_+^{p^{\mathrm{RT}}}, \ \boldsymbol{y}^{\mathrm{RT}} \in \{0,1\}^{q^{\mathrm{RT}}}; \\ & \boldsymbol{\vartheta} \in \Theta, \ \boldsymbol{\vartheta} \in \mathbb{R}_+^{2+3N}; \end{aligned} \quad \xRightarrow{\ \vartheta\ } \quad \begin{aligned} v^\star(\boldsymbol{\vartheta}) = & \min_{\boldsymbol{x}^{\mathrm{RT}}, \boldsymbol{y}^{\mathrm{RT}}} \ \boldsymbol{c}^\top \boldsymbol{x}^{\mathrm{RT}} + \boldsymbol{d}^\top \boldsymbol{y}^{\mathrm{RT}} \\ \text{s.t.} \ & \boldsymbol{A}\boldsymbol{x}^{\mathrm{RT}} + \boldsymbol{E}\boldsymbol{y}^{\mathrm{RT}} \leq \boldsymbol{F}\boldsymbol{\vartheta} + \boldsymbol{b}; \\ & \boldsymbol{x}^{\mathrm{RT}} \in \mathbb{R}_+^{p^{\mathrm{RT}}}, \ \boldsymbol{y}^{\mathrm{RT}} \in \{0,1\}^{q^{\mathrm{RT}}}; \\ & \boldsymbol{\vartheta} \in \Theta, \ \boldsymbol{\vartheta} \in \mathbb{R}_+^{2+3N}; \end{aligned} \quad \xRightarrow{\ \vartheta\ } \quad \begin{aligned} v^\star(\boldsymbol{\vartheta}) = & \min_{\boldsymbol{x}^{\mathrm{RT}}, \boldsymbol{y}^{\mathrm{RT}}} \ \boldsymbol{c}^\top \boldsymbol{x}^{\mathrm{RT}} + \boldsymbol{d}^\top \boldsymbol{y}^{\mathrm{RT}} \\ \text{s.t.} \ & \boldsymbol{A}\boldsymbol{x}^{\mathrm{RT}} + \boldsymbol{E}\boldsymbol{y}^{\mathrm{RT}} \leq \boldsymbol{F}\boldsymbol{\vartheta} + \boldsymbol{b}; \\ & \boldsymbol{x}^{\mathrm{RT}} \in \mathbb{R}_+^{p^{\mathrm{RT}}}, \ \boldsymbol{y}^{\mathrm{RT}} \in \{0,1\}^{q^{\mathrm{RT}}}; \\ & \boldsymbol{\vartheta} \in \Theta, \ \boldsymbol{\vartheta} \in \mathbb{R}_+^{2+3N}; \end{aligned}$$

About 3 minutes per step

⇕

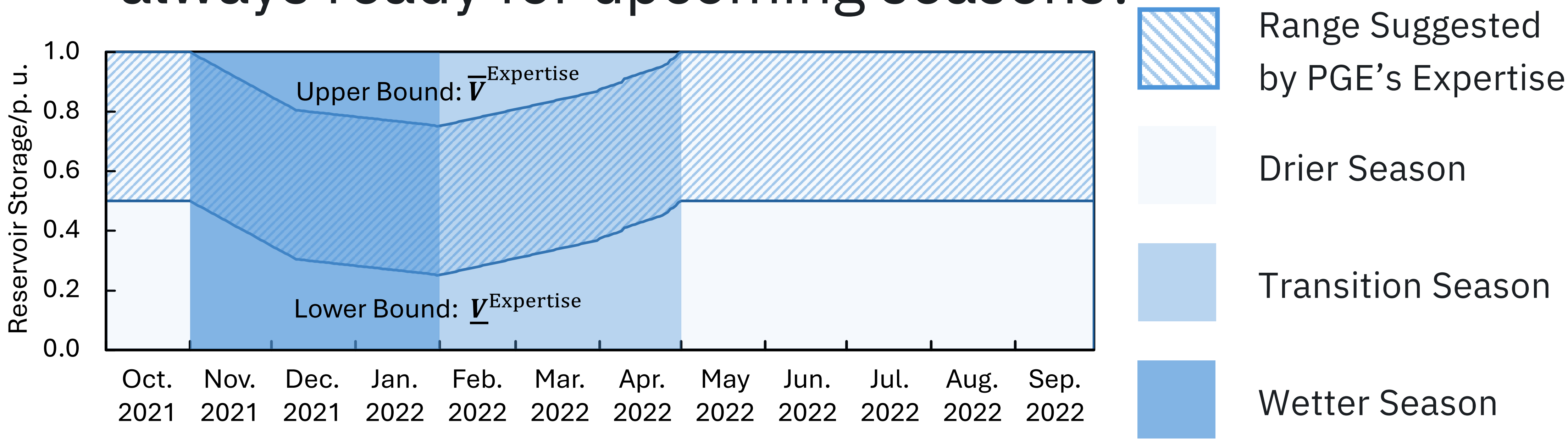
About 2 seconds per step

$$\begin{cases} \boldsymbol{x}^{\mathrm{RT}\star} = \boldsymbol{A}_1^{\mathrm{AS}^{-1}} \boldsymbol{F}_1^{\mathrm{AS}} \boldsymbol{\vartheta} + \boldsymbol{A}_1^{\mathrm{AS}^{-1}} \boldsymbol{b}_1^{\mathrm{AS}} & \text{if } \boldsymbol{\vartheta} \in \Theta_1^{\mathrm{CR}}; \\ \vdots & \\ \boldsymbol{x}^{\mathrm{RT}\star} = \boldsymbol{A}_R^{\mathrm{AS}^{-1}} \boldsymbol{F}_R^{\mathrm{AS}} \boldsymbol{\vartheta} + \boldsymbol{A}_R^{\mathrm{AS}^{-1}} \boldsymbol{b}_R^{\mathrm{AS}} & \text{if } \boldsymbol{\vartheta} \in \Theta_R^{\mathrm{CR}}; \end{cases} \xRightarrow{\ \vartheta\ } \begin{cases} \boldsymbol{x}^{\mathrm{RT}\star} = \boldsymbol{A}_1^{\mathrm{AS}^{-1}} \boldsymbol{F}_1^{\mathrm{AS}} \boldsymbol{\vartheta} + \boldsymbol{A}_1^{\mathrm{AS}^{-1}} \boldsymbol{b}_1^{\mathrm{AS}} & \text{if } \boldsymbol{\vartheta} \in \Theta_1^{\mathrm{CR}}; \\ \vdots & \\ \boldsymbol{x}^{\mathrm{RT}\star} = \boldsymbol{A}_R^{\mathrm{AS}^{-1}} \boldsymbol{F}_R^{\mathrm{AS}} \boldsymbol{\vartheta} + \boldsymbol{A}_R^{\mathrm{AS}^{-1}} \boldsymbol{b}_R^{\mathrm{AS}} & \text{if } \boldsymbol{\vartheta} \in \Theta_R^{\mathrm{CR}}; \end{cases} \xRightarrow{\ \vartheta\ } \begin{cases} \boldsymbol{x}^{\mathrm{RT}\star} = \boldsymbol{A}_1^{\mathrm{AS}^{-1}} \boldsymbol{F}_1^{\mathrm{AS}} \boldsymbol{\vartheta} + \boldsymbol{A}_1^{\mathrm{AS}^{-1}} \boldsymbol{b}_1^{\mathrm{AS}} & \text{if } \boldsymbol{\vartheta} \in \Theta_1^{\mathrm{CR}}; \\ \vdots & \\ \boldsymbol{x}^{\mathrm{RT}\star} = \boldsymbol{A}_R^{\mathrm{AS}^{-1}} \boldsymbol{F}_R^{\mathrm{AS}} \boldsymbol{\vartheta} + \boldsymbol{A}_R^{\mathrm{AS}^{-1}} \boldsymbol{b}_R^{\mathrm{AS}} & \text{if } \boldsymbol{\vartheta} \in \Theta_R^{\mathrm{CR}}; \end{cases}$$

A DRL-Based Mid-Term Planning for Renewable-Integrated Cascaded Hydropower

- **Questions to be addressed**

  2) How can reservoir storage be ensured that it is always ready for upcoming seasons?

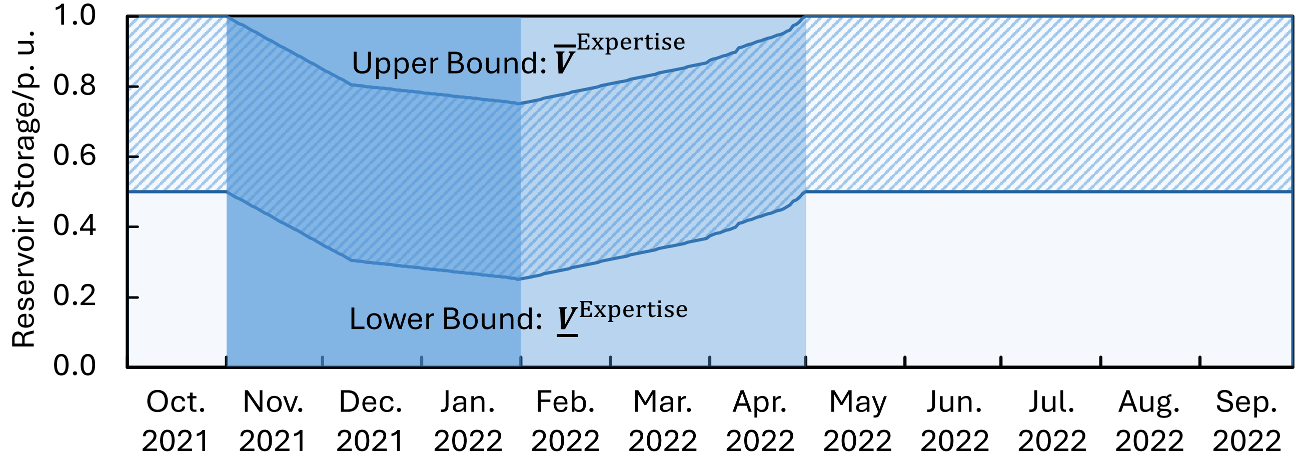


A DRL-Based Mid-Term Planning for Renewable-Integrated Cascaded Hydropower

- **Expertise-based mechanism**

The game Space Impact

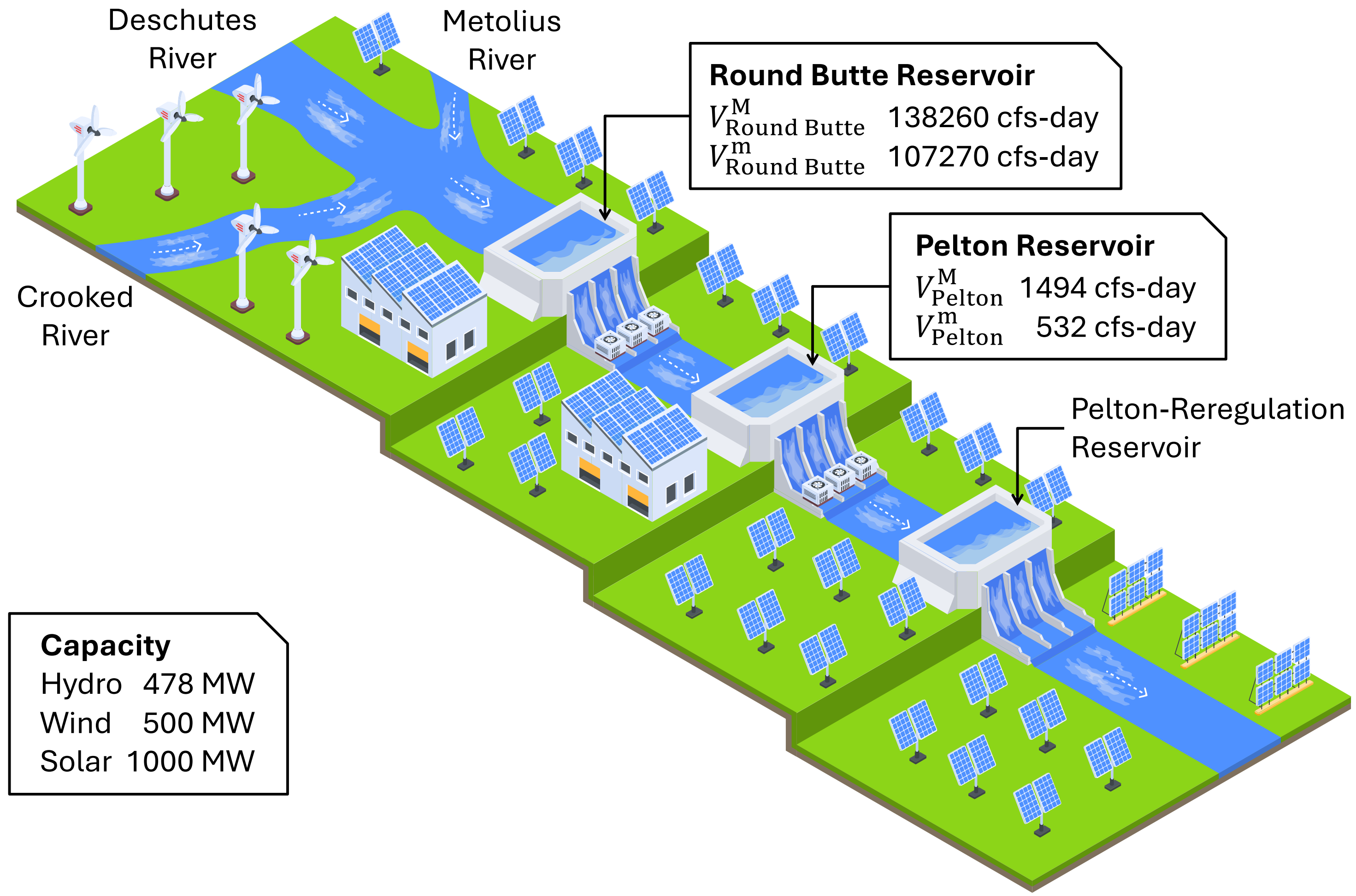
**Image source: https://giphy.com/*



Avoid crashes into the ceiling ($\overline{V}^{\text{Expertise}}$) and floor ($\underline{V}^{\text{Expertise}}$) of the tunnel

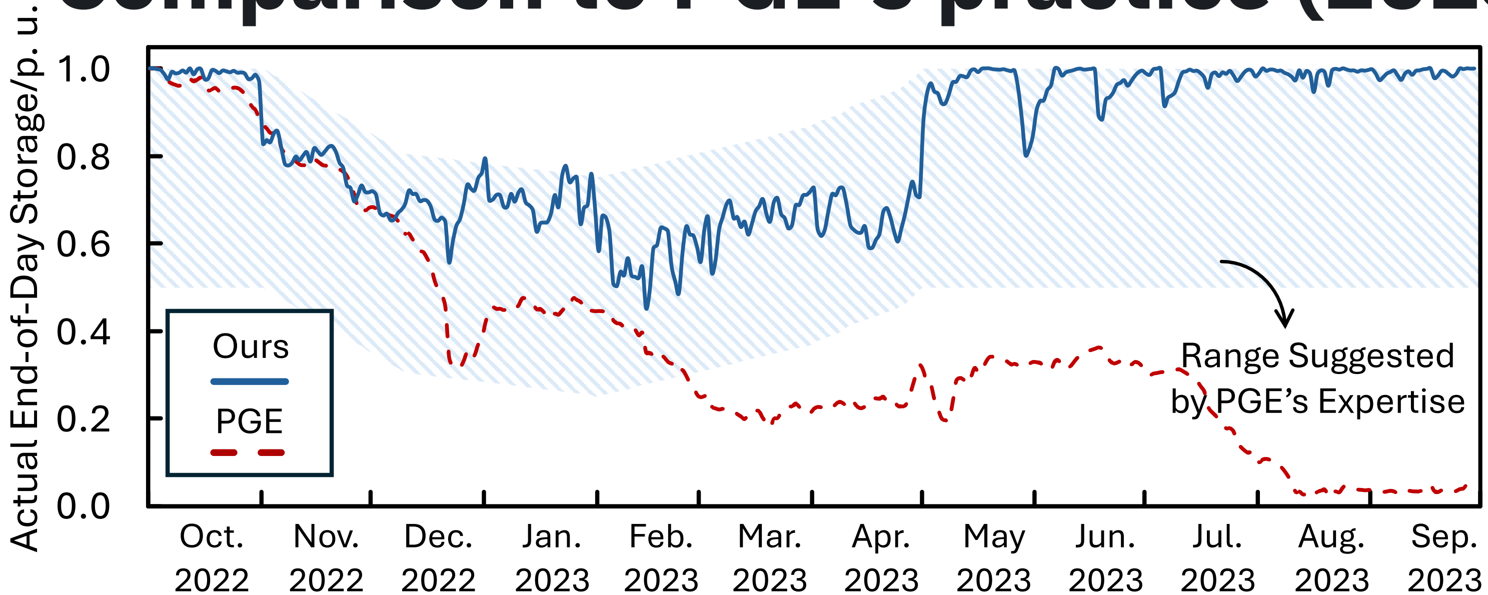
A DRL-Based Mid-Term Planning for Renewable-Integrated Cascaded Hydropower

- **PGE's Pelton Round Butte System with renewable integration**



A DRL-Based Mid-Term Planning for Renewable-Integrated Cascaded Hydropower

- **Comparison to PGE's practice (2023 water year)**



Method	Net Revenue/\$10⁶
Presented Method	325.8
PGE's Practice	323.3

- Not "crashes" (always be ready for the upcoming seasons)
- Improvement of 0.8% (\$2.5×10⁶)

DRL-Based Mid-Term Planning for Renewable-Integrated Self-Scheduling Cascaded Hydropower

- **Summary**
  1) Target improving revenue by enhancing mid-term planning strategies
  2) Mid-term planning and short-term operations are integrated in a closed-loop manner via DRL
  3) Expertise-based mechanism for ensuring seasonal adaptivity
  4) Multi-parametric programming for accelerating training
  5) Annual revenue improvement of 0.8% (\$$2.5\times10^6$)

Summary

1. Closed-loop predict-and-optimize (CPO) is an idea against open-loop predict-then-optimize

2. CPO-based prediction model for unit commitment: Lower operating cost

3. CPO-based mid-term planning approaches for cascaded hydropower: Higher operating revenue

Papers

- **CPO for UC**

[1] **X. Chen**, Y. Yang, Y. Liu, and L. Wu, "Feature-Driven Economic Improvement for Network-Constrained Unit Commitment: A Closed-Loop Predict-and-Optimize Framework," in *IEEE Transactions on Power Systems*, 2022.

[2] **X. Chen**, Y. Liu, and L. Wu, "Towards Improving Unit Commitment Economics: An Add-On Tailor for Renewable Energy and Reserve Predictions," in *IEEE Transactions on Sustainable Energy*, 2024.

- **CPO for CHP scheduling**

[3] **X. Chen**, Y. Liu, Z. Zhong, N. Fan, Z. Zhao, and L. Wu, "A Carryover Storage Quantification Framework for Mid-Term Cascaded Hydropower Planning: A Portland General Electric System Study," under review of *IEEE Transactions on Sustainable Energy*, 2024.

[4] **X. Chen**, Y. Liu, N. Fan, Z. Zhao, and L. Wu, "DRL-Based Mid-Term Planning of Renewable-Integrated Self-Scheduling Cascaded Hydropower for Short-Term Wholesale Market Participation," under review of *IEEE Transactions on Sustainable Energy*, 2024.

[5] Y. Liu, **X. Chen**, N. Fan, Z. Zhao, and L. Wu, "Stochastic Day-Ahead Operation of Cascaded Hydropower Systems with Bayesian Neural Network-based Scenario Generation: A Portland General Electric System Study," in *International Journal of Electrical Power & Energy Systems*, 2023.

Presentations

- **CPO for UC**
  1) Operation Research Live Talk, China, 2021
  2) IEEE PES Grid Edge Technologies Conference & Exposition, San Diego, California, 2023
  3) Federal Energy Regulatory Commission Fourteenth Annual Software Conference, Washington, DC, 2023
  4) IEEE PES General Meeting, Orlando, Florida, 2023
  5) Stevens Institute of Technology ECE Ph.D. Research Exposition, 2024
  6) Sichuan University, Chengdu, China, 2024
- **CPO for CHP scheduling**
  7) INFORMS Annual Meeting, Phoenix, Arizona, 2023

STEVENS
INSTITUTE OF TECHNOLOGY
1870

Thank You