Integrating Variable Wind Power Using a Hydropower Cascade

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Motivation

- Hydropower is an enormously flexible resource
- Capable of deploying stored water energy very quickly
- Fewer start-up and shut-down restrictions than thermal power plants
- Renewable (but not necessarily environmentally friendly)
- **How much flexibility can hydropower provide in real-time operations for balancing the variability from wind power?**
- **How do the operations of a coordinated wind-hydro system differ from those of a hydro-only system?**

Motivation

- Hydropower is an enormously flexible resource
- Capable of deploying stored water energy very quickly
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- **How much flexibility can the Mid-Columbia hydropower system provide in real-time operations for balancing the variability from wind power in the Pacific Northwest?**
- **How do the operations of a coordinated wind-hydro system differ from those of a hydro-only system?**

Mid-Columbia System

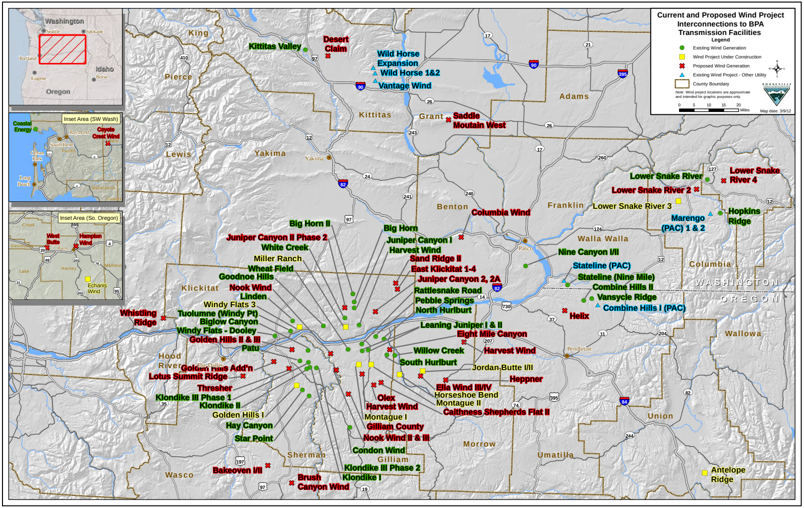
Source: Army CoE

Mid-Columbia System

	Name	Type	Head (m)	MW
1	Grand Coulee	Federal	100	6809
2	Chief Joseph	Federal	53	2069
3	Wells	Municipal	21	774
4	Rocky Reach	Municipal	27	1300
5	Rock Island	Municipal	13	629
6	Wanapum	Municipal	23	1038
7	Priest Rapids	Municipal	23	956

We have one year of timestamped data for this system, with a temporal resolution of five minutes

Wind Power in the Pacific Northwest



Source: BPA

Modeling: Model Predictive Control

$$\mathbf{x}(k+1) = A \cdot \mathbf{x}(k) + B \cdot \mathbf{u}(k) \quad \text{for } k = 0, 1, ..., K-1$$

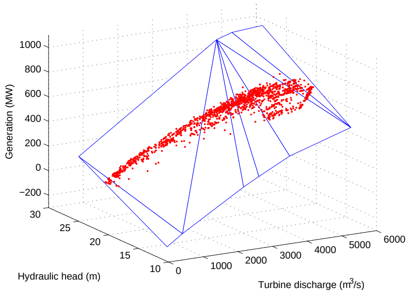
- System model is developed to predict the response of the system $\mathbf{x}$ to a sequence of control inputs $\mathbf{u}$
- The system is optimized over a time-horizon $k = 0, 1, ..., K$
- The control sequence that gives the best performance over the time-horizon is computed
- Only the first-step of this control sequence is applied
- The reaction of the system is observed and the process is repeated at the next time-interval

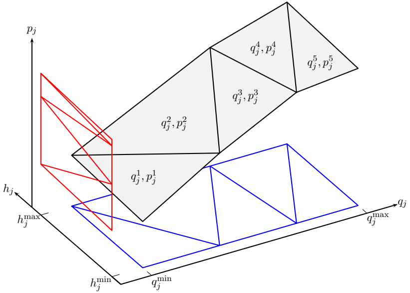
Modeling: Hydraulic Model

- State variables: reservoir elevation, tailrace elevation
- Control variables: turbine discharge, spill, natural inflow/sideflow
- Reservoir elevation is a linear function of inflows and outflows
  - Surface area assumed to be constant
  - Storage is only sufficient for a few hours of operation
  - Run-of-river with some flexibility
- Tailrace elevation is a function of turbine discharge, spill, and downstream forebay elevation (i.e., encroachment)
  - Tailrace elevation changes more than forebay elevation
- Travel time of water between plants is considered
  - Tens of minutes
- **Constraints on turbine discharge, spill, forebay elevation, change in turbine discharge, change in spill**

Modeling: Hydropower Generation

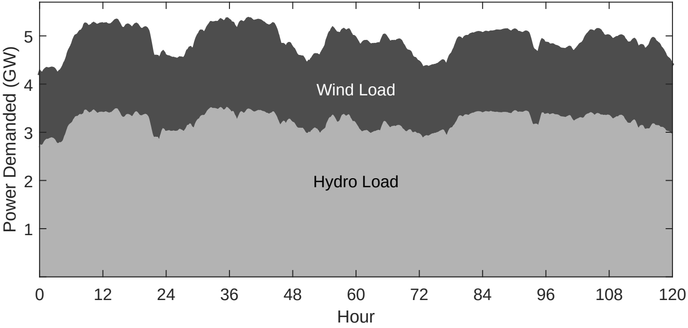
$$p(q, h) = \kappa \cdot \eta_t(q) \cdot \eta_g(q) \cdot q \cdot h$$





Modeling: Hydro Power Balance

$$\sum_{j=1}^{J} p_j(k) = p_{\mathrm{hydroload}}(k)$$



Modeling: Wind power

$$\sum_{j=1}^{J} p_j(k) + \epsilon(k) = p_{\text{hydroload}}(k) + p_{\text{windload}}(k) - p_{\text{wind}}(k)$$

- ϵ is wind curtailment if negative
- ϵ is load curtailment if positive
- p_{wind} is wind generation
- p_{windload} is additional wind load
- We use BPA wind generation data for p_{wind} and BPA balancing area load data for p_{windload} scaled such that...

$$\sum_{n=1}^{N} p_{\text{windload}} = \sum_{n=1}^{N} p_{\text{wind}}$$

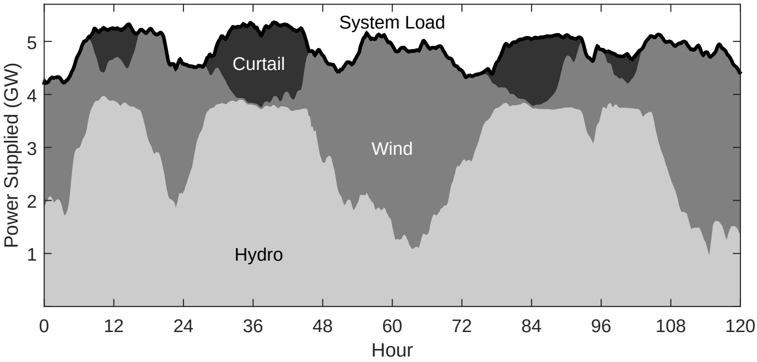
Modeling: Objective function

$$\min_{q_j, s_j, \epsilon} \left\{ \sum_{k=0}^{K-1} \sum_{j=1}^{J} \left[a_j \cdot q_j(k)^2 + c_j \cdot s_j(k)^2 \right] + \sum_{k=0}^{K-1} d \cdot \epsilon(k)^2 \right\}$$

$$a_j = c_j = \left(\frac{\eta_j}{\eta_{j+1}} \cdot \frac{\Psi_{j+1}}{\Psi_j} \right)^2 \qquad d \gg a_j$$

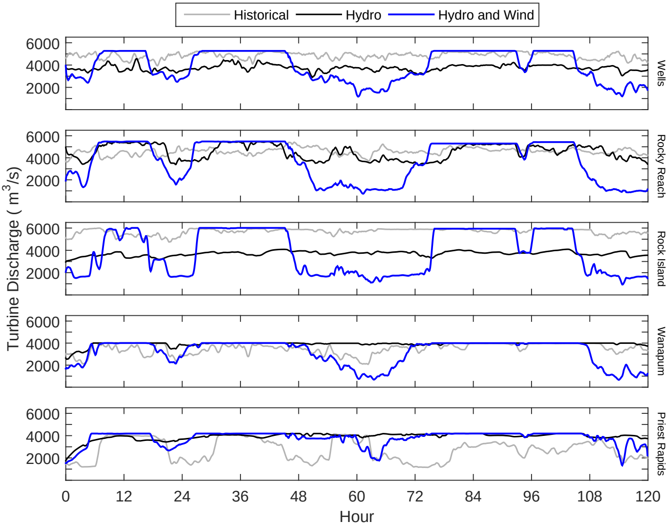
- Weight turbine discharge and spill to encourage the transfer of water from large surface area reservoirs to small surface area reservoirs
- Choose the weight d on ϵ large to put a heavy penalty on load or wind curtailments

Case Study: 120 Hours in July 2012

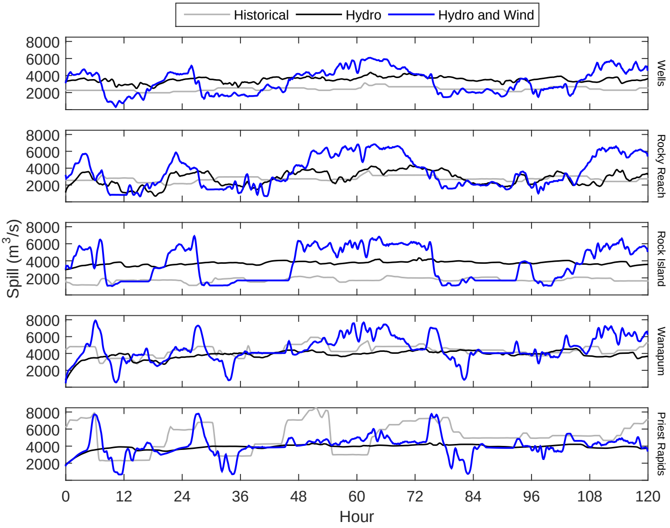


Load curtailment when wind generation was low and hydro hit its upper capacity limit

Case Study: 120 Hours in July 2012



Case Study: 120 Hours in July 2012



Case Study: Statistics

- 4884 MW_{avg} of load
- 2874 MW_{avg} of hydro generation
- 1664 MW_{avg} of wind generation
- 346 MW_{avg} of load curtailment
- 357 MW_{avg} of spilled water
- 5396 MW peak load and 3838 MW peak wind generation
- 34% wind energy penetration
- 71% wind capacity penetration

Case Study: Ramping

		Ramping Score		
j	Name	Hist.	Hydro	H+W
1	Wells	9.3	7.8	24.3
2	Rocky Reach	9.4	17.0	26.6
3	Rock Island	6.6	5.6	31.3
4	Wanapum	10.9	2.9	15.5
5	Priest Rapids	21.6	6.0	13.9

Ramping score is proportional to the sum of the absolute change in the turbine discharge

Future Work

- Apply this framework across different hydraulic conditions, system constraints, and wind/load scenarios
- What are the appropriate metrics? Ramping, unit cycling, spilled water energy, spilled wind energy, etc.?
- What should the additional load from wind look like? Should it be normal load, hourly blocks, on-peak blocks, off-peak blocks?
- Should thermal power plants be modeled?
- **What does it mean when we say that we want to balance wind using hydropower? What are the best evaluation metrics?**

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Questions?

Thank you!