Modeling and Optimizing Flexibility Across Coupled Infrastructure Systems

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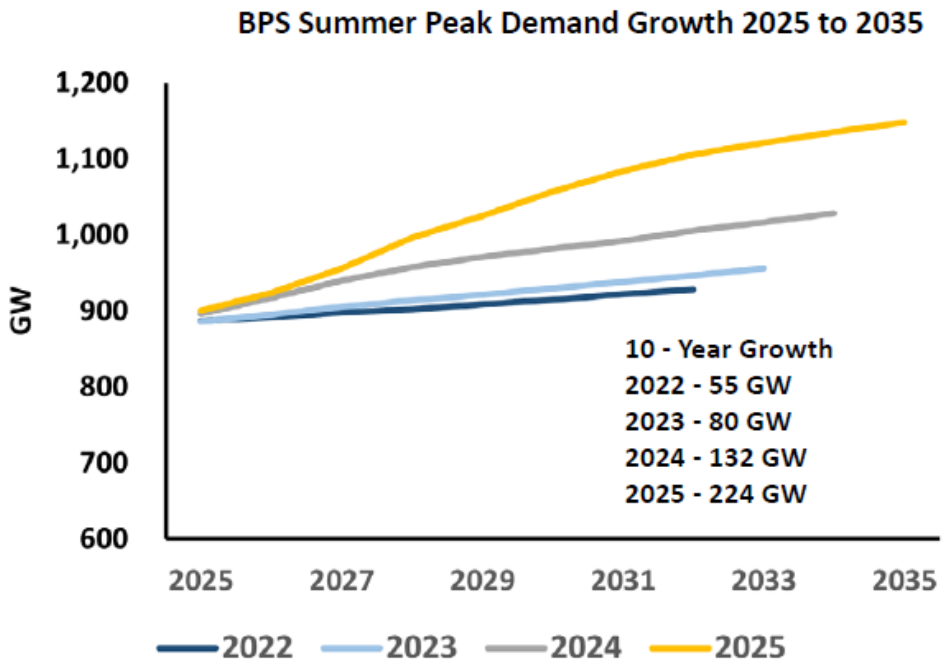
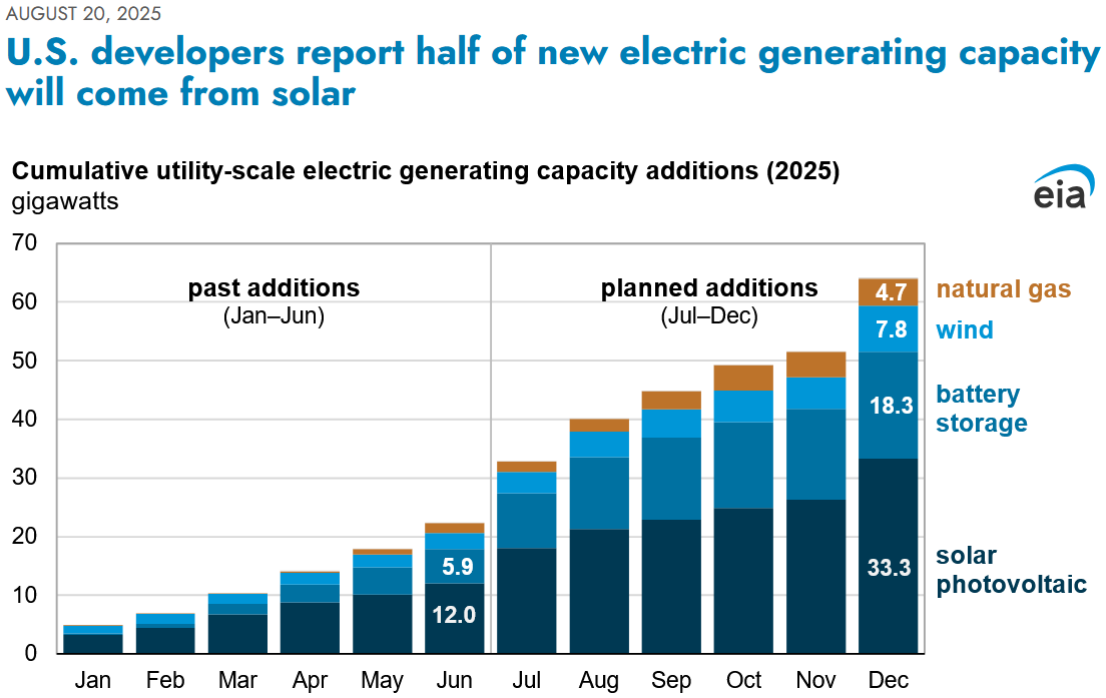
Challenges in power sector

Growing variability and demand require new sources of grid flexibility.

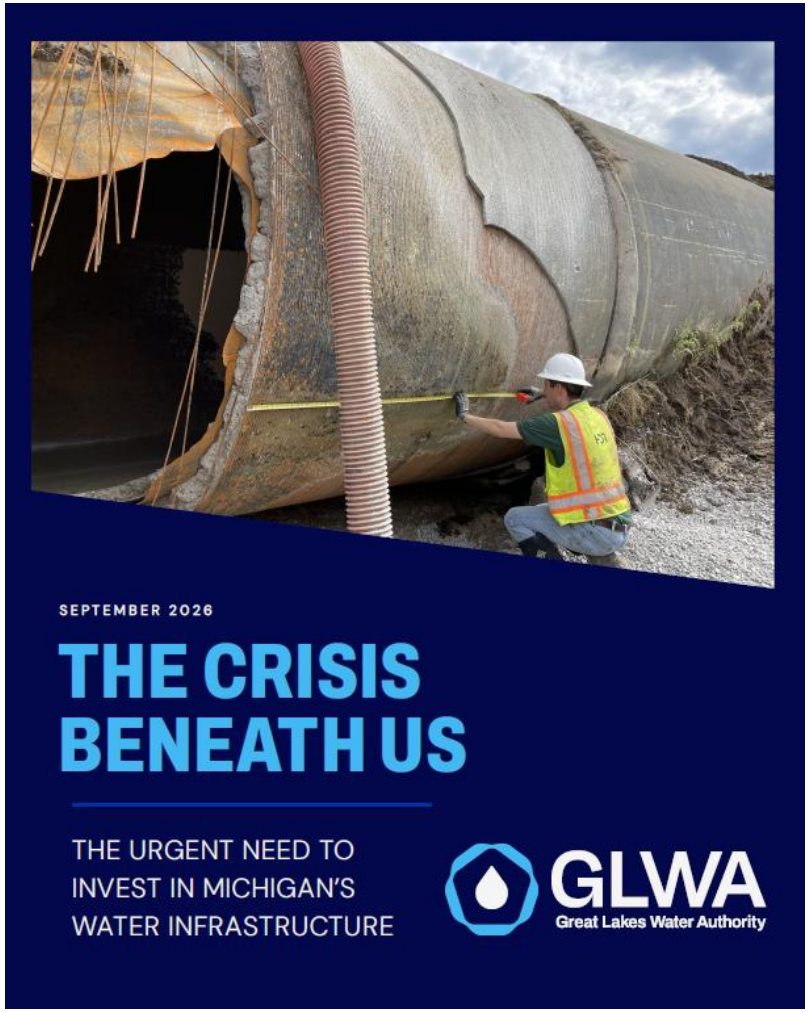


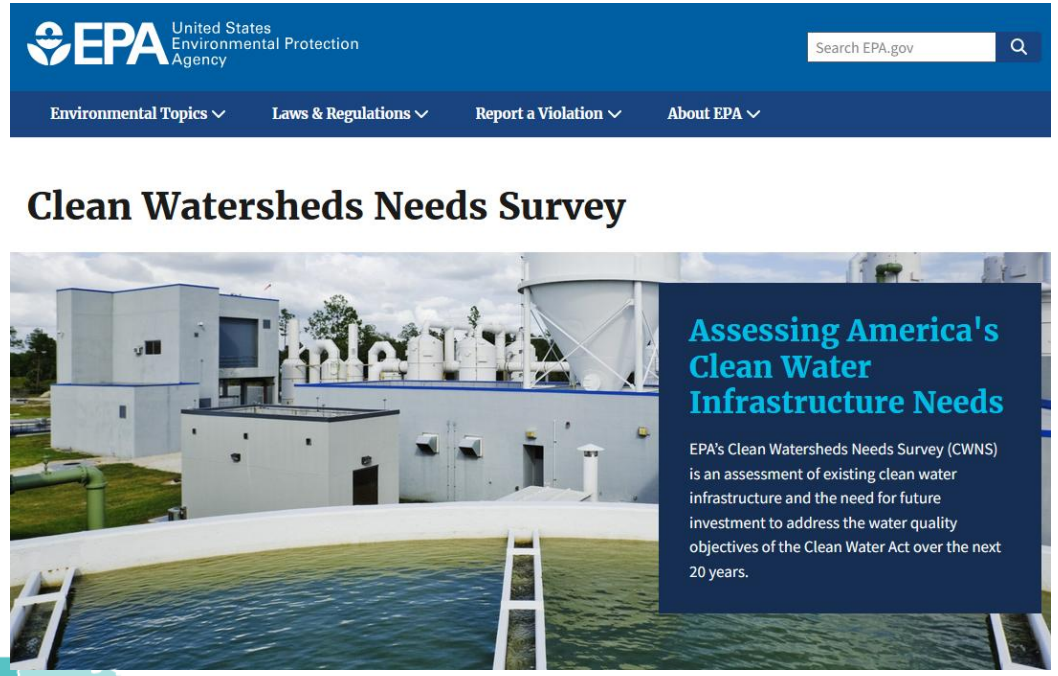
Source: NERC LTRA 2025

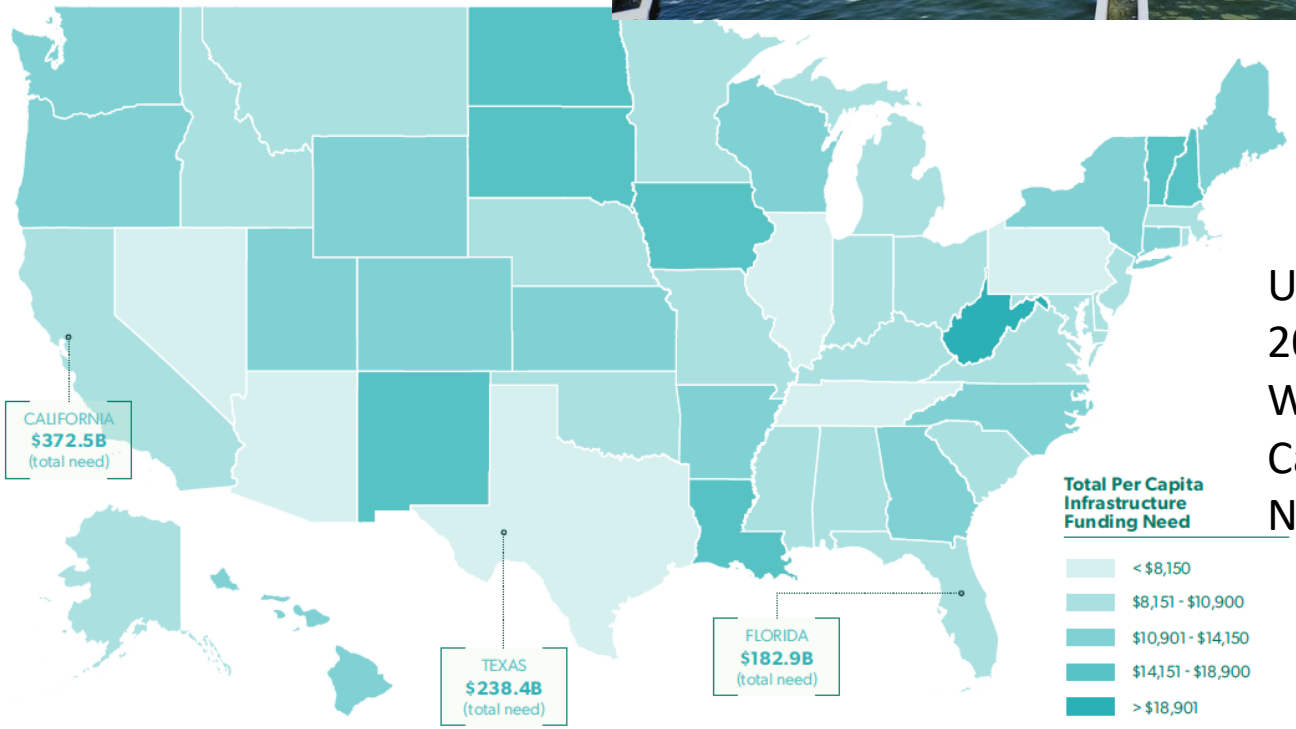


Source: EIA

Challenges in other sectors







US Water Alliance: 20-Year Per-Capita Water Infrastructure Capital Funding Needs by State

Opportunity – Coordination between sectors

- Coordinating infrastructure operation with electric grid needs creates new opportunities for both systems.
- Examples
  - Power and drinking water
  - Power and wastewater treatment
- Benefits
  - Existing infrastructure
  - Energy-intensive loads
  - Interconnected and flexible resources
  - (SCADA systems)

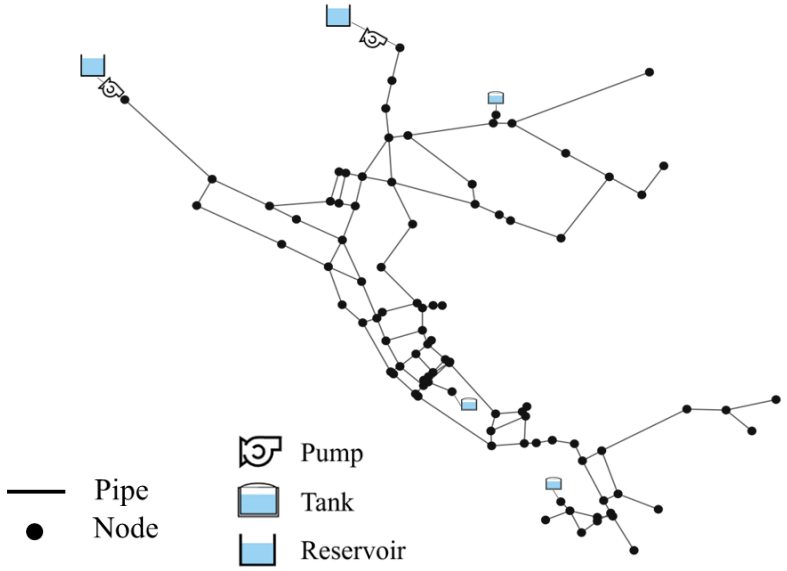
Outline

Case study 1: Power + Drinking Water
Optimizing water pumping to provide demand response and grid services

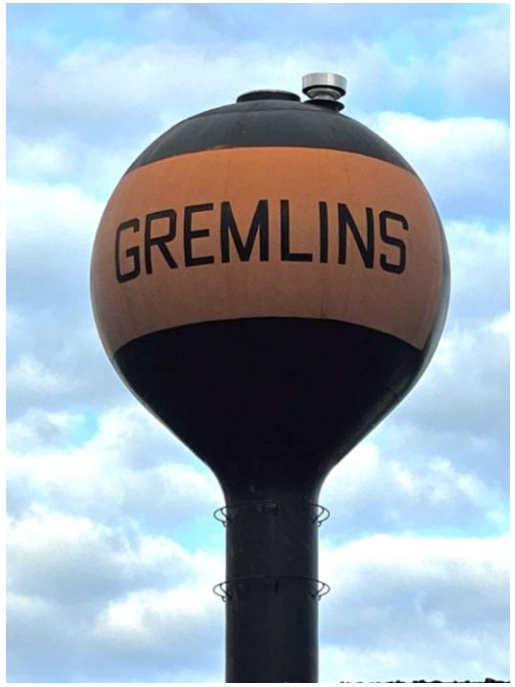
Case study 2: Power + Food
Optimizing agrivoltaic tracking under flexible interconnection agreements

Focus: Power & Drinking Water Distribution

- Spatial and temporal load shifting
- Water supply pumps as flexible loads
- Subject to water flow constraints

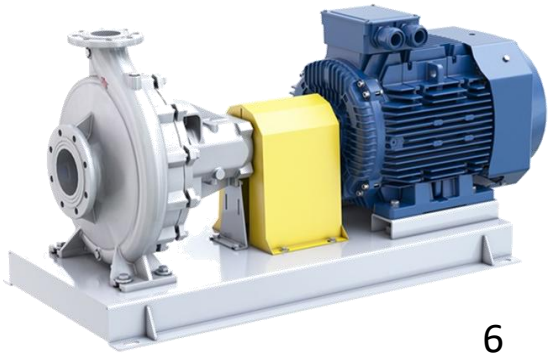


EPANET Net3



Water Towers in Houghton, MI and Ann Arbor, MI

Centrifugal Pump (Sulzer EN733)



Focus: Power & Drinking Water Distribution

How can we leverage pumps and tanks in the water distribution network to support the power grid while…

- ensuring water flow constraints are met?
- minimizing total operational cost?

minimize Cost of Scheduled Water Network Operation & Flexibility

Scheduled Pump Operation $\boldsymbol{P}$
Frequency regulation capacity $\boldsymbol{F}$

subject to: Water Flow Constraints
→ schedule $\boldsymbol{P}$
→ min/max frequency regulation $\boldsymbol{P} \pm \boldsymbol{F}$

Pump Operation Strategies

regulation revenue

RULE

- Heuristic, rule-based operation
- Current approach

For example, turn on pump x when the tank level is below y.

OWF

- Optimal water pumping formulation
- Solve for pump status and setting

min $\boldsymbol{\pi_1^\top P}$
s.t. Water Flow ($\boldsymbol{P}$)

pump electricity costs

OWF + FR

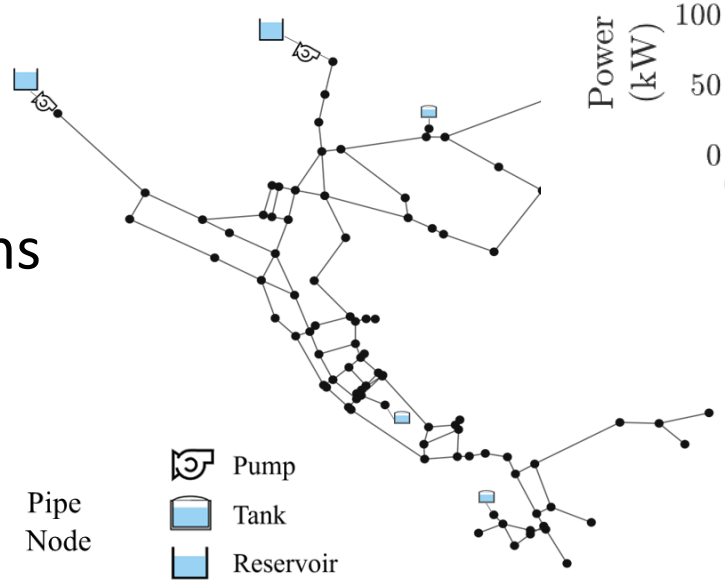
- Optimal water pumping and frequency regulation provision formulation
- Solve for scheduled pump status and setting and frequency regulation capacity

min $\boldsymbol{\pi_1^\top P - \pi_2^\top F}$
s.t. Water Flow ($\boldsymbol{P}$)
Water Flow ($\boldsymbol{P \pm F}$)

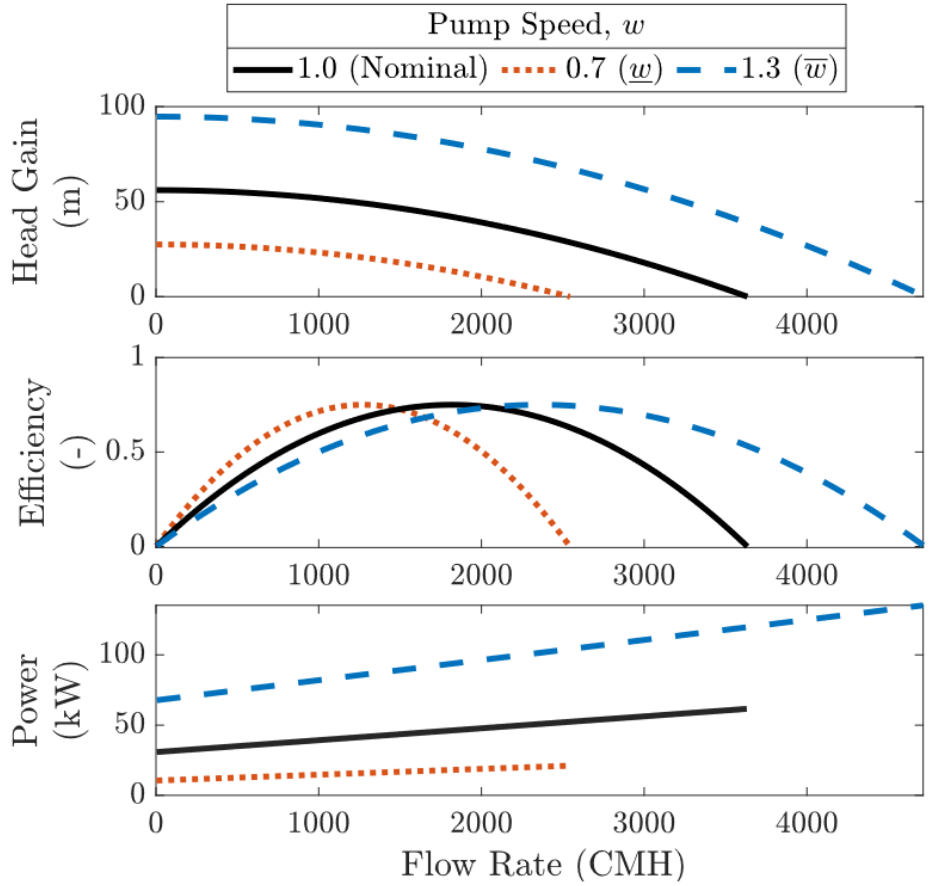
Water Flow Constraints

Characterized by hydraulic head H_j^t and volumetric flow rate x_{ij}^t

- Solve for: variable speed pumps
  - Speed $\underline{w} \leq w^t \leq \overline{w}$
  - Status $z_{ij}^t \in \{0,1\}$
- Operational limits
  - Hydraulic heads at junctions
  - Flow rates through pumps
  - Water storage tank limits



EPANET Net3



Optimal Pumping Formulation – Solution Approach

- Mixed-Integer Nonconvex Program
- Iterative, mixed-integer linear program

$$H_i^t - H_j^t = k_{ij} \cdot x_{ij}^t \cdot |x_{ij}^t|^{\nu-1}$$

$$H_i^t - H_j^t = f_{ij}^{t,0} + x_{ij}^t$$

$$f_{ij}^{t,0} := x_{ij}^t \cdot (k_{ij}|x_{ij}^t|^{\nu-1} - 1)$$

Algorithm 1 Iterative OWF MILP Algorithm

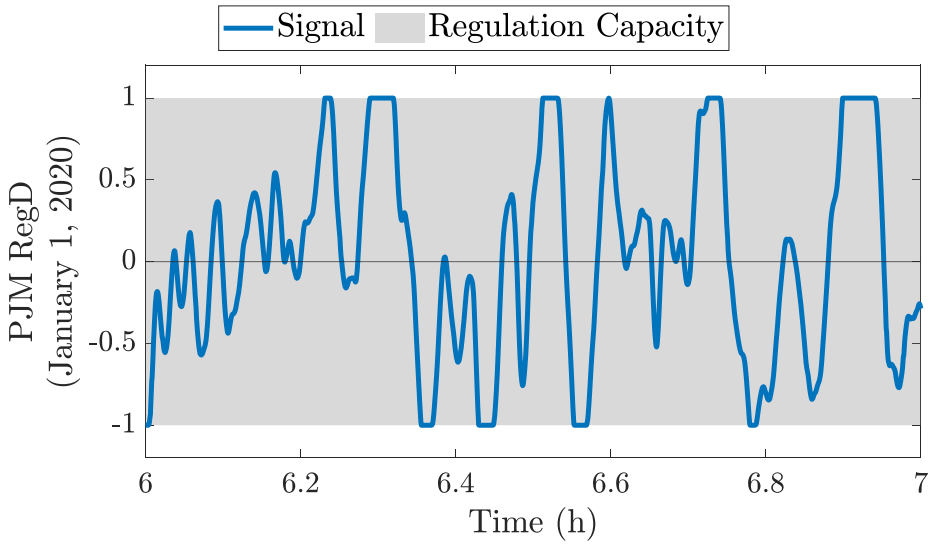
Require: Water network topology, initial tank conditions $H_j^{t=0}\ \forall\ j \in \mathcal{S}$, and forecasted electricity prices $\pi_{ij}^t\ \forall\ ij \in \mathcal{P}, t \in \mathcal{T}$ and water demands $d_j^t\ \forall\ j \in \mathcal{J}, t \in \mathcal{T}$

Output: Pump power consumption p_{ij}^t, status z_{ij}^t, and speed $w_{ij}^t\ \forall\ ij \in \mathcal{P}, t \in \mathcal{T}$

1: **Set** $k \leftarrow 0$, tolerance, maxIter, and error
2: **Initialize** $\langle \boldsymbol{f} \rangle_k$ in (25)-(26), and $\langle \boldsymbol{x} \rangle_k$.
3: **while** error $\geq$ tolerance OR $k \leq$ maxIter **do**
4: $\quad k \leftarrow k + 1$
5: $\quad$ Solve $(\text{OWF})_k$ using $\langle \boldsymbol{f} \rangle_{k-1}$ to obtain $\langle \boldsymbol{x}_{ij}^t \rangle_k$.
6: $\quad$ Calculate $\langle \boldsymbol{f} \rangle_k$ given $\langle \boldsymbol{x}_{ij}^t \rangle_k$ in (25)-(26).
7: $\quad$ Calculate error $:= ||\langle \boldsymbol{f} \rangle_k - \langle \boldsymbol{f} \rangle_{k-1}||_2$.
8: **end while**
9: The water system operator sets pump status $z_{ij}^t := \langle z_{ij}^t \rangle_k$ and speed $w_{ij}^t := \langle (W_{ij}^t)^{(1/2)} \rangle_k$.

Optimal Pumping Formulation – Solution Approach

- Load adjusts power consumption based on baseline power p_{ij}^t, committed regulation capacity F_{ij}^t, and ISO signal $\tilde{s} \in [-1,1]$
- Use affinity laws to set real-time pump speed, which approximate how changes in pump speed impact the pump characteristics

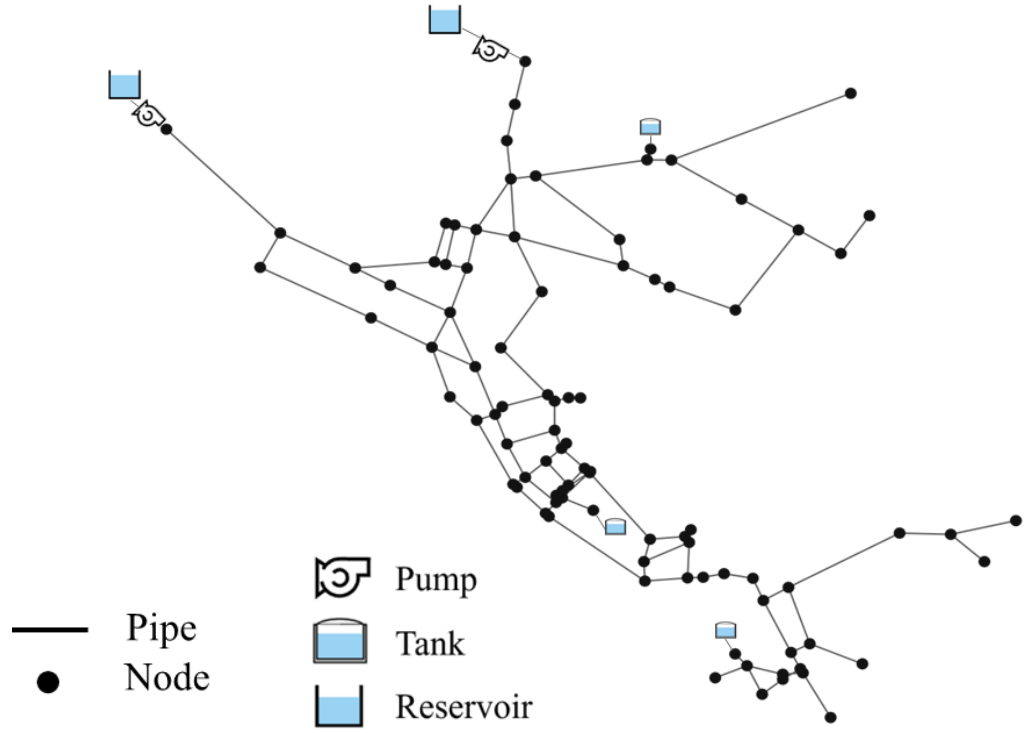


$$\frac{x_1}{x_2} = \frac{w_1}{w_2}, \qquad \frac{\hat{H}_1}{\hat{H}_2} = \left(\frac{w_1}{w_2}\right)^2, \qquad \frac{p_1}{p_2} = \left(\frac{w_1}{w_2}\right)^3$$

$$\hat{w}_{ij} = w_{ij}^t \cdot \left(1 + \frac{F_{ij}^t \tilde{s}}{p_{ij}^t}\right)^{1/3}$$

Optimal Pumping Case Study

- Net3 [1]
- Compare Rule-based, OWF, and OWF+FR
- PJM RegD signal
- Performance evaluated in EPANET 2.2/WNTR hydraulic simulator using 2-second time step



Topology of Net3 water distribution network [1]

[1] Rossman et al., 2020.

Case Study: Cost Comparison

Speed?	Control Strategy	Electricity Cost ($)	Frequency Regulation Profit ($)	Total Costs ($)
Fixed	(Rule)	208.02	-	208.02
Variable	(OWF)	83.59	-	83.59
Variable	(OWF+FR)	107.55	44.91	62.64

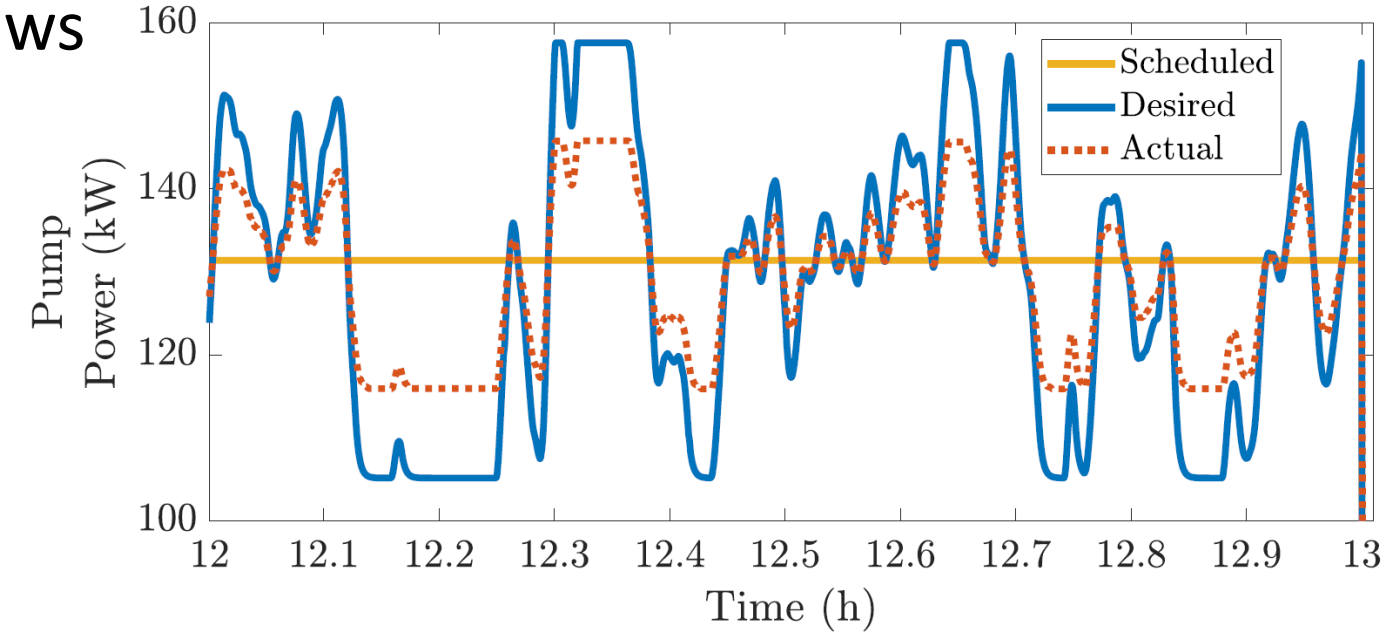
60-70% cost decrease!

- Optimal pump strategies (OWF and OWF+FR) significantly less expensive than rule-based strategy.
  - Partially optimization problem over heuristic rule-based operation
  - Partially variable speed pumps (a good idea)

    **15-30% typical energy savings for variable speed pumps [NYSERDA 2010]*
- Reduced operational cost participating in regulation

Case Study: Evaluating Frequency Regulation

- Hydraulic simulation, where pump speed adjustments are based off the affinity laws

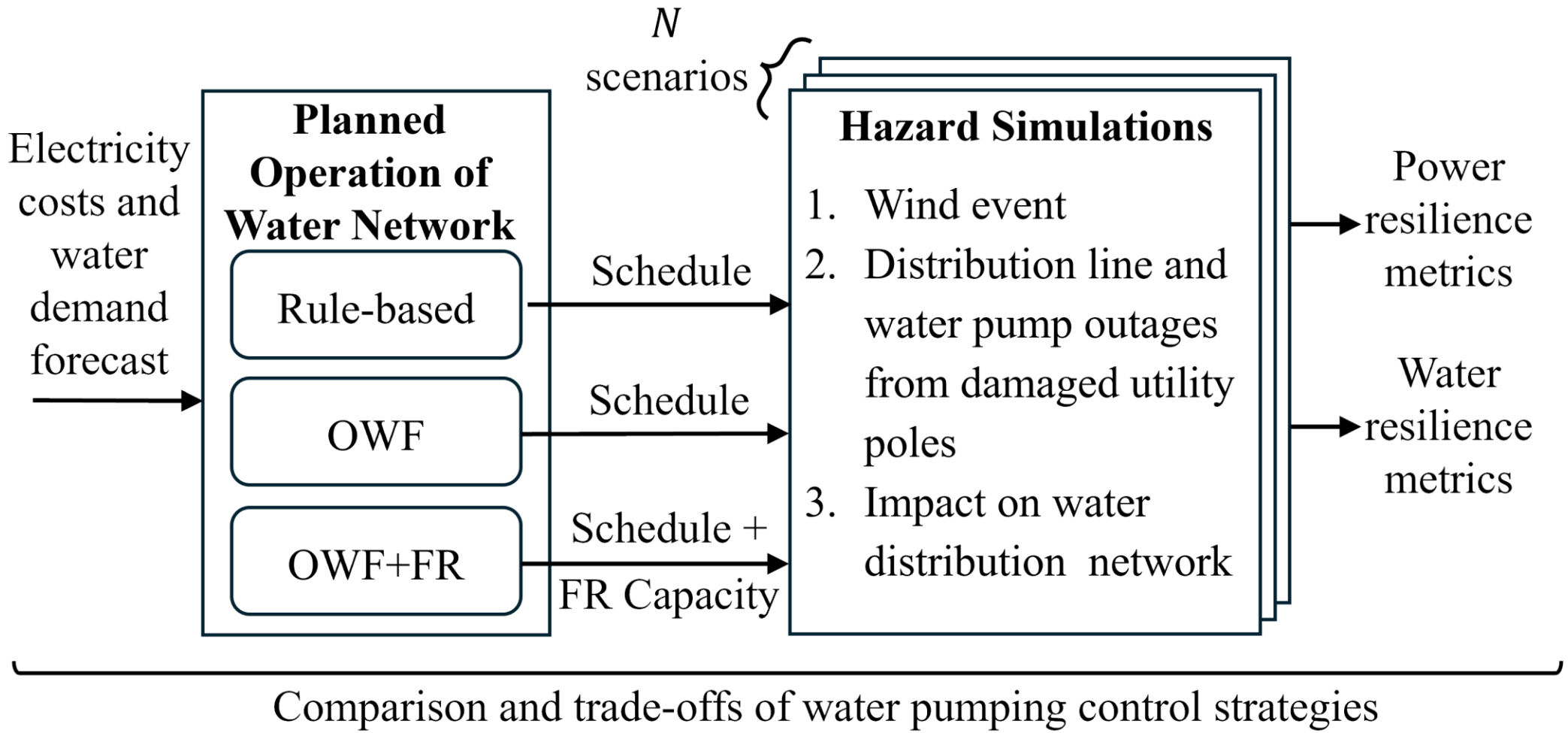


- **Pumps generally follow the frequency regulation signal,** but the **affinity laws appear to consistently over-estimate the real-time pump power deviation that is provided.**
- Alternative approaches: incorporate feedback with PI controller

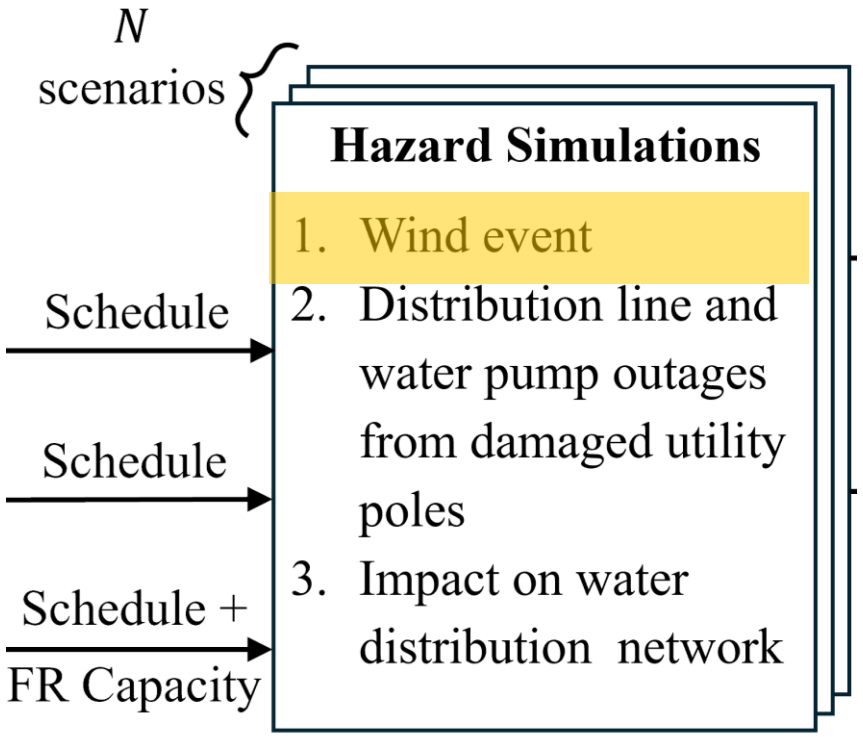
Better or worse off?

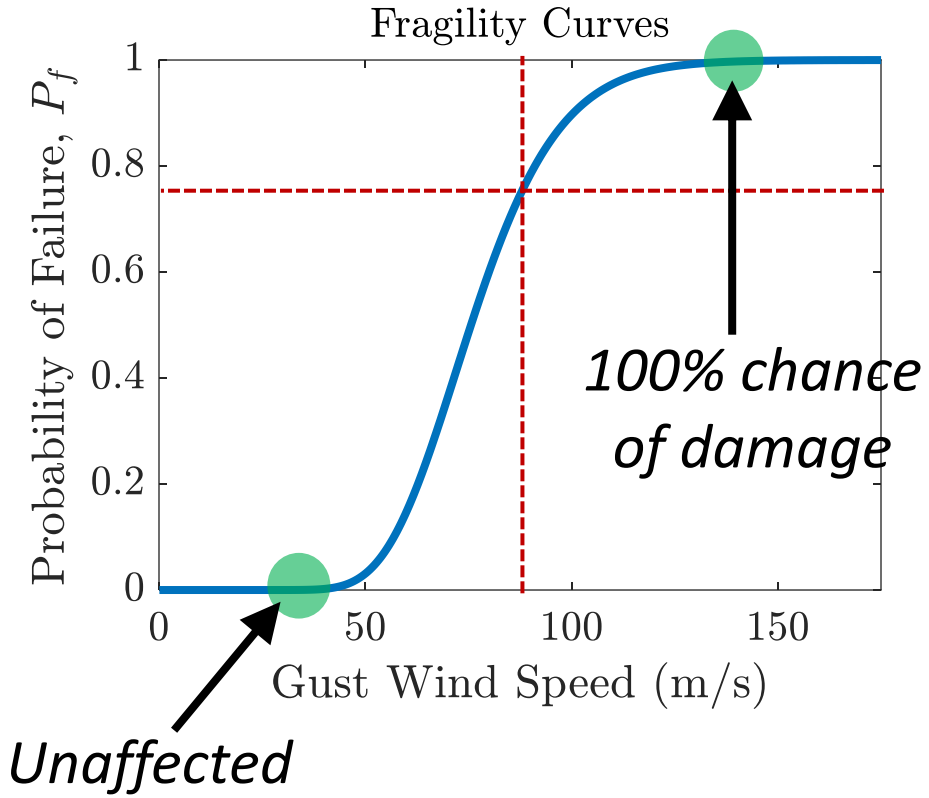
Do optimal pumping strategies negatively impact the ability of the water distribution network to respond to and recover from a hazard event?

Evaluating operational resilience of water pumping strategies



Hazard Simulations



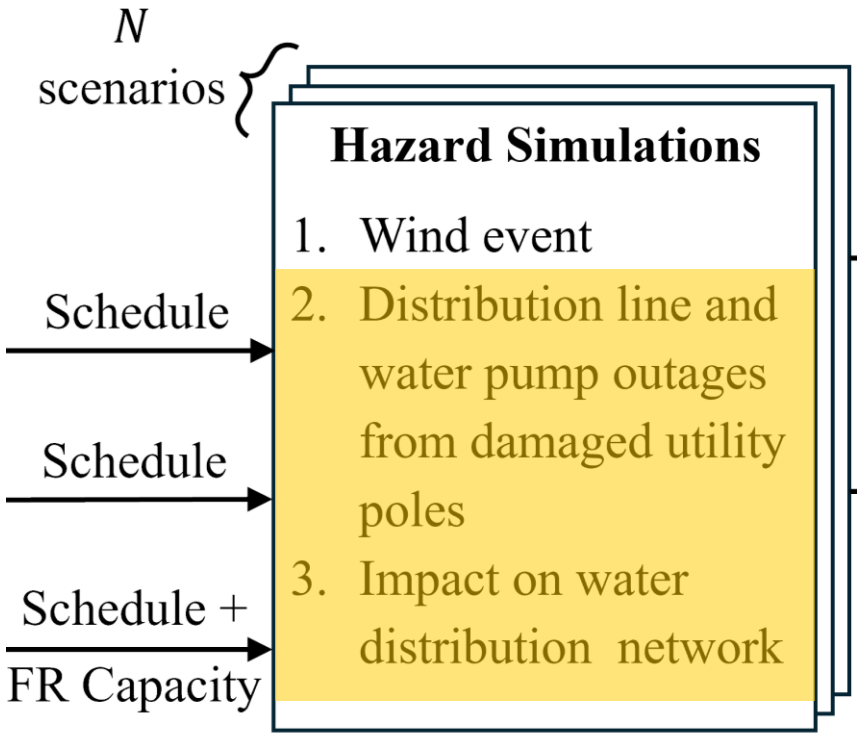


- Multi-period wind event
- N scenarios of utility pole damage status using fragility curves [1]

Pole Fails: $P_f(V^t, y, \theta, A_c, h) > r^t$

[1] Darestani and Shafieezadeh, 2019.

Hazard Simulations



- Map damaged poles to bus/line and pump outages
- EPANET hydraulic simulator within WNTR [1] for all N scenarios for all control strategies

WNTR
Water Network Tool for Resilience

[1] Klise et al., 2017.

Operational Resilience

Wind-induced time-varying performance curve

Resilience metric for scenario n

$$R_n = \frac{\sum_{t \in \mathcal{T}} P^t_{\mathrm{W},n}}{\sum_{t \in \mathcal{T}} P^t_{\mathrm{N}}} \quad \forall\, n = 1 \ldots N$$

Normal operation time-varying performance curve

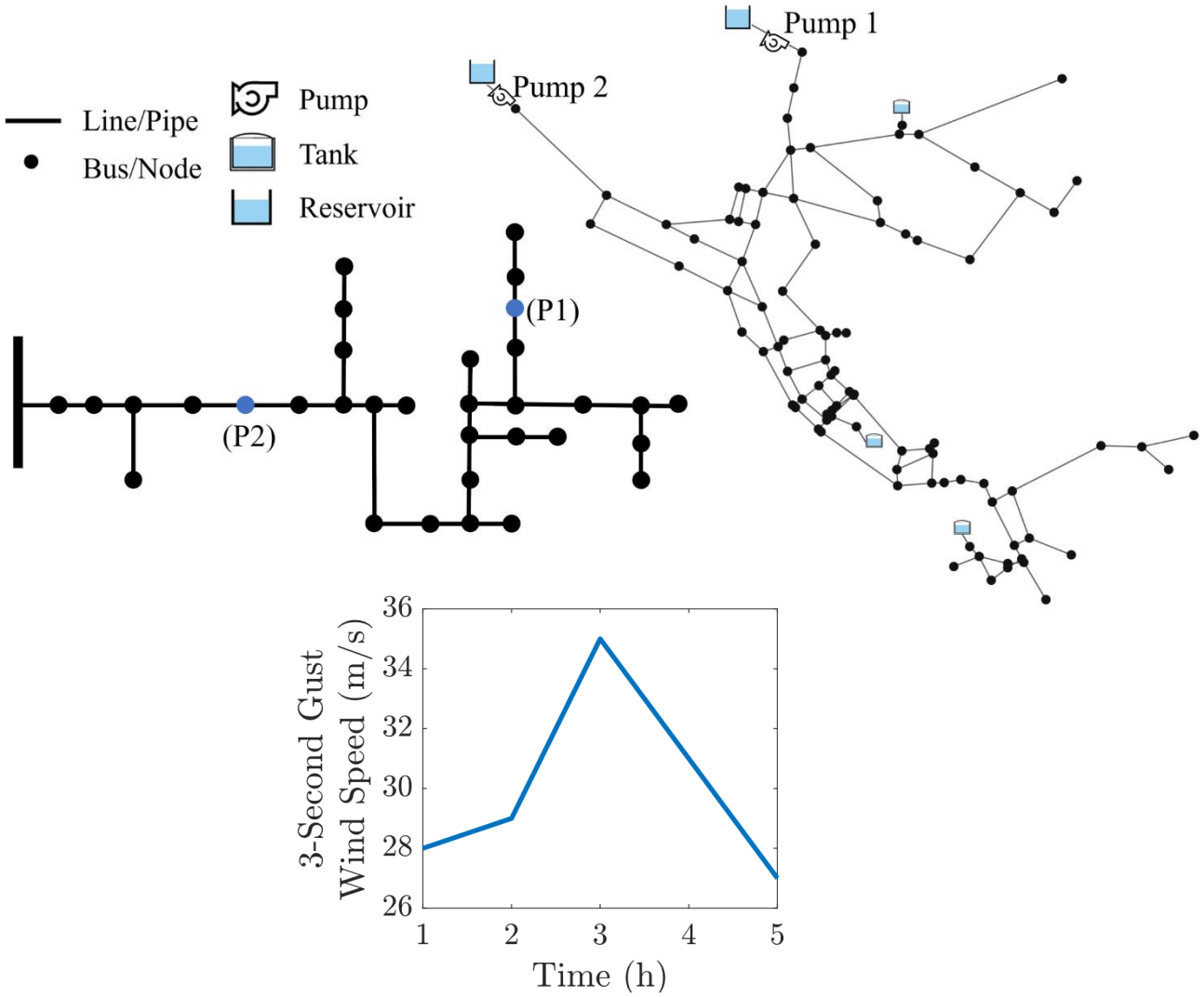
Power resilience metrics → Number of active lines

Water resilience metrics → Water service availability

Test Case

- 5 hour duration wind event, multiplier used to consider different wind speed intensities 100%, 125%, 140%, and 150%
- Time horizon: 72 hours
- PJM RegD signal
- 500 scenarios

Topology of Coupled Power Distribution Network [1] and Water Distribution Network [2]

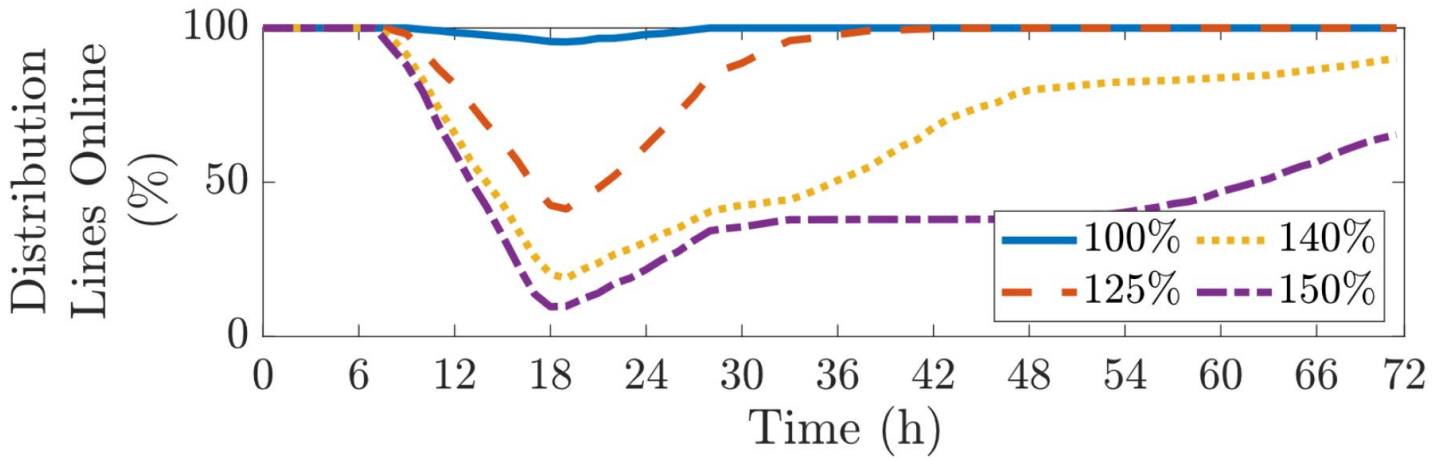


[1] Kersting, 2001.

[2] Rossman et al., 2020.

Test Case: Power Network

Wind Speed (%)	R_{lines} (%)
100	99.38
125	89.78
140	67.42
150	47.90



- Average active line resilience metrics over 500 scenarios
- As expected, as wind speed increases, the connected lines resilience metric decreases
- Performance curves visualize storm severity implications

Test Case: Water Network

Average Water Distribution Network Resilience Metrics

Wind Speed	R_{wsa} (%)			R_{tank} (%)		
	Rule	OWF	OWF+FR	Rule	OWF	OWF+FR
100	99.91	99.89	99.85	98.35	99.08	93.20
125	97.31	96.54	96.51	75.98	58.58	73.36
140	77.83	73.17	77.58	47.74	36.92	45.82
150	46.49	37.66	47.06	24.76	25.16	22.71

- Resilience of the water network decreases as the wind hazard intensity increases
  - Tanks depleted
  - Rule-based operation limited to 40-60% tank capacity
- OWF+FR generally better than OWF
  - Allocating reserve capacity to frequency regulation may help provide a buffer in water distribution network operation against hazards

Test Case: Take-aways

- We compared the performance and operational resilience of the water network given a wind-based event under different control strategies.
- Cost of optimal water pumping strategies significantly less expensive than traditional, heuristic approach.
- While operational resilience of optimal pumping policies degrade in optimal control strategies, resilience constraints can be incorporated
- Operational resilience of water network improved when providing frequency regulation compared to just minimizing cost.

Outline

Case study 1: Power + Drinking Water
Optimizing water pumping to provide demand response and grid services

Case study 2: Power + Food
Optimizing agrivoltaic tracking under flexible interconnection agreements

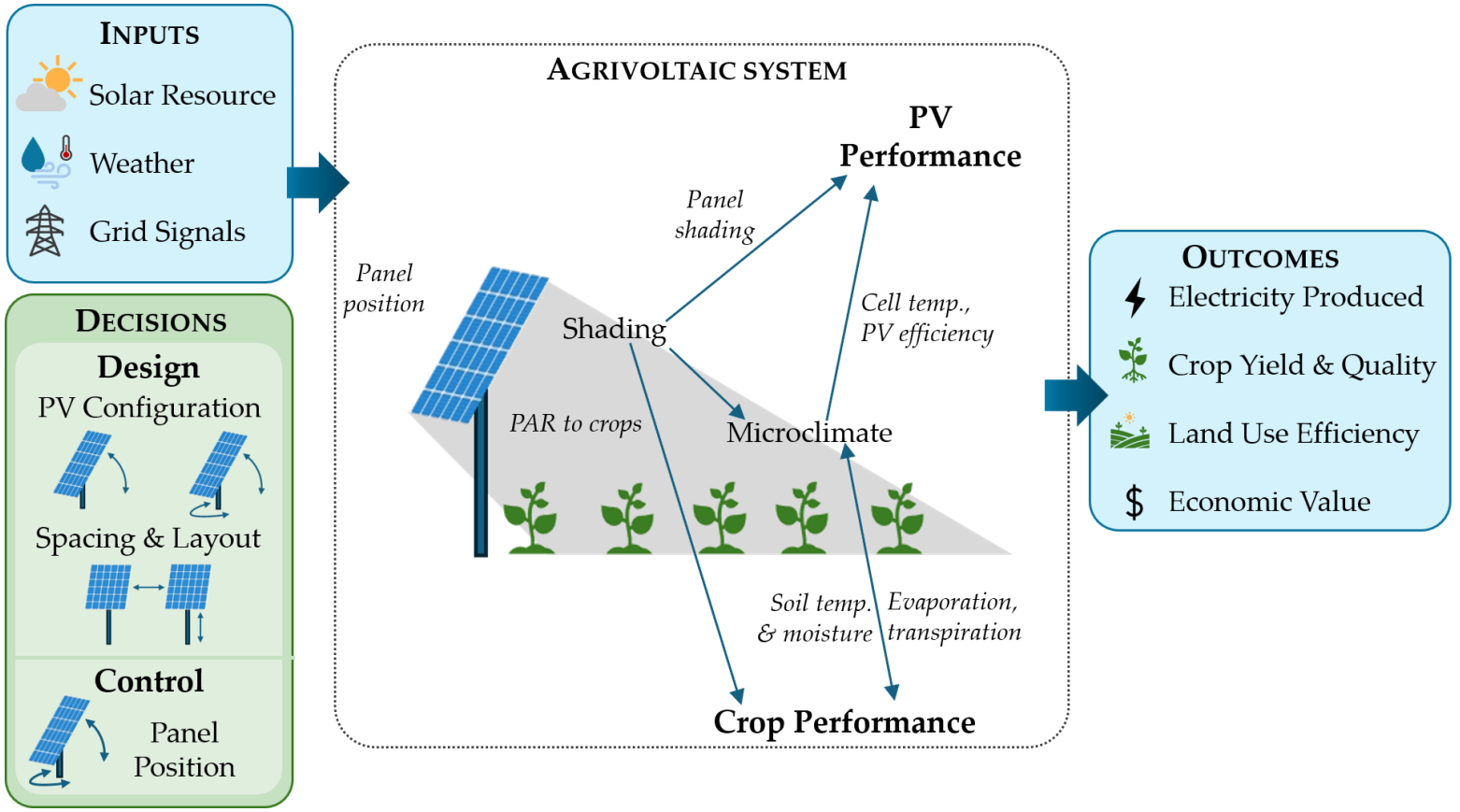
Agrivoltaics

- Concept: PV co-located with crops, grazing pasture, or pollinator fields
- Reduce the competing land use demands of energy and food production
- Mutual benefits and tradeoffs
  - Increased land use efficiency, improving PV panel efficiency
  - Crop response v. PV power production

Source: Alliant Energy Solar Farm at Iowa State

Operational control of agrivoltaics

- **Panel position impacts both crop growth and PV power production**
- Multiple outcomes, multiple objectives
- Existing strategies include sun-tracking/anti-tracking
- **Question: How should tracking be controlled?**

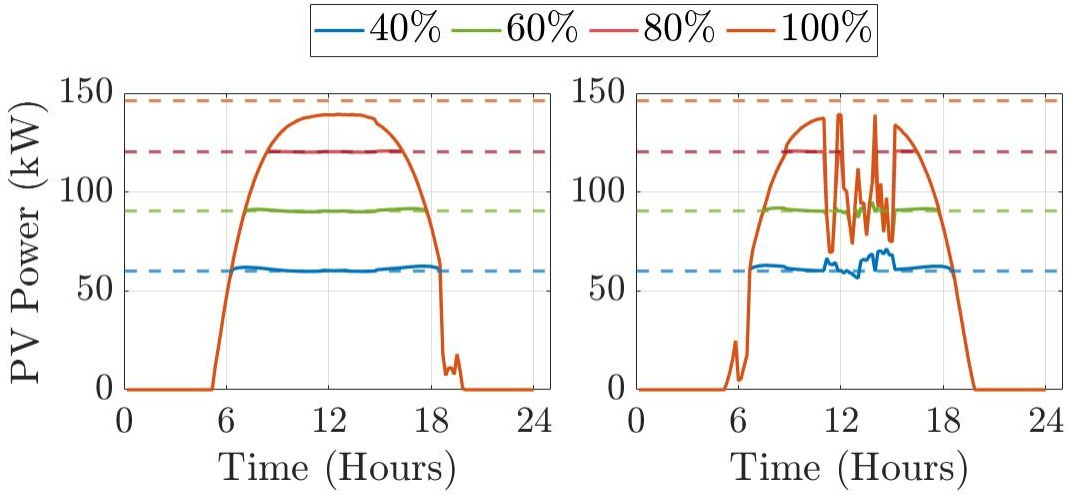


Impact of export limits on power and yield

- As the export limit decreases, PV energy production decreases but crop yield increases
- On relaxation accuracy: export limit violations are infrequent over 60-day period
  - Violations increase under tighter limits and cloudy conditions ($I^t_{\text{diffuse}} + I^t_{\text{reflect}} \gg I^t_{\text{direct}}$)
  - $>$ 50% limit: 0-0.13% of time periods
  - $\leq$ 50% limit: 0.93-1.88% of time periods
- Inverter curtailment can supplement panel adjustments when additional power reduction is needed to meet the export limit

IMPACT OF EXPORT LIMITS ON PV ENERGY AND CROP YIELD

Power Limit (%)	Energy (kWh)	Crop Yield (t/ha)
100	73,501	1.874
90	72,090	1.885
80	68,534	1.937
70	63,706	2.017
60	57,583	2.129
50	50,382	2.276
40	42,257	2.455



Concluding remarks

- Power grid is interconnected with the water and agriculture sector. By leveraging these interactions, water supply and agrivoltaics can be used as flexible grid assets.
- Drinking water systems: Optimizing pump operations can reduce electricity costs, where providing grid service may improve operational resilience while maintaining water service.
- Agrivoltaic systems: Optimizing solar tracking can balance electricity generation and crop productivity while accommodating grid export limits under flexible interconnection agreements.

Questions?

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