# Optimal Sizing of Behind-the-Meter Energy Storage with Stochastic Load and PV Generation for Islanded Operation

David Copp, Tu Nguyen, Ray Byrne

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# Publications in 2018

## Distributed Control of Energy Storage

- F. Wilches-Bernal, D. A. Copp, G. Bacelli, R. H. Byrne, ***Structuring the Optimal Output Feedback Control Gain: A Soft Constraint Approach.*** Proc. IEEE Conference on Decision and Control (CDC), 2018.

- F. Wilches-Bernal, D. A. Copp, I. Gravagne, D. A. Schoenwald, ***Stability Criteria for Power Systems with Damping Control and Asymmetric Feedback Delays.*** Proc. 50th North American Power Symposium (NAPS), 2018.

- D. A. Copp, F. Wilches-Bernal, D. A. Schoenwald, I. Gyuk, ***Power System Damping Control via Injections from Distributed Energy Storage.*** Proc. International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2018.

## Optimization of Energy Storage (EMS, market participation, sizing and scheduling)

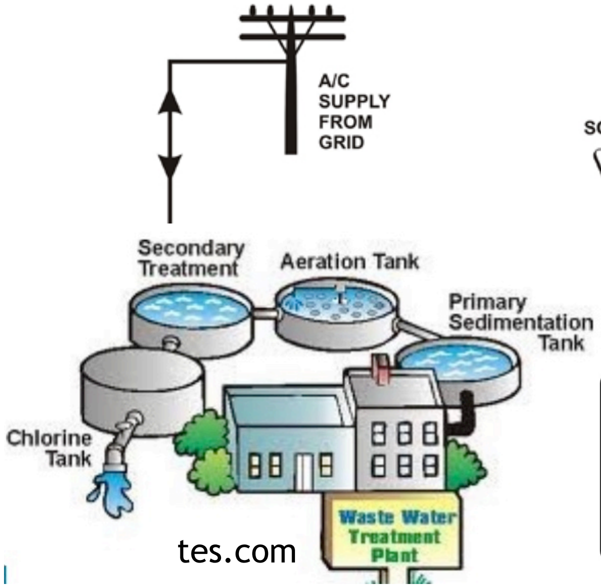
- D. A. Copp, T. A. Nguyen, R. H. Byrne, ***Real-Time Energy Management of Energy Storage with Stochastic Load and Generation in Markets.*** Under Review, 2018.

- T. A. Nguyen, D. A. Copp, R. H. Byrne, B. R. Chalamala, ***Optimal Market Participation of Energy Storage Considering Nonlinear Models.*** Under Review, 2018.

- D. A. Copp, T. A. Nguyen, R. H. Byrne, ***Optimal Sizing of Behind-the-Meter Energy Storage with Stochastic Load and PV Generation for Islanded Operation.*** Proc. IEEE PES General Meeting, 2018.

- R. H. Byrne, T. A. Nguyen, D. A. Copp, R. Concepcion, B. R. Chalamala, I. Gyuk, ***Opportunities for Energy Storage in CAISO: Day-Ahead and Real-Time Market Arbitrage.*** Proc. International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2018.

# Optimizing Behind-the-Meter Energy Storage



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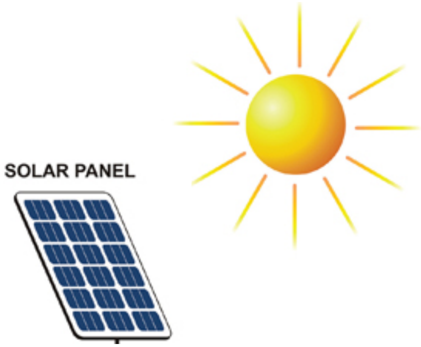

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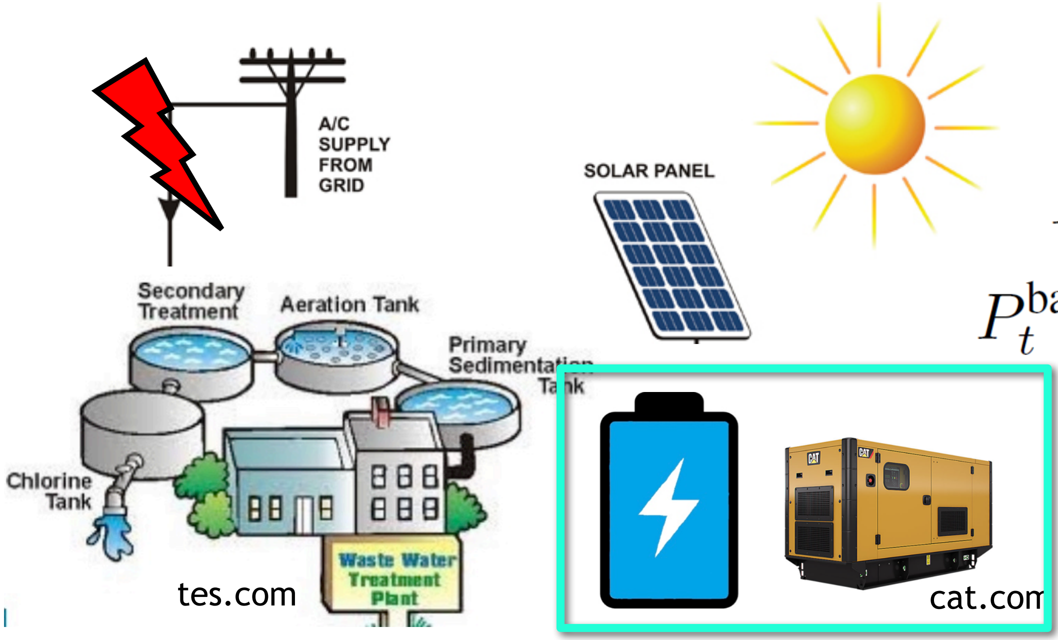

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$$P_t^{\text{balance}} = P_t^{\text{net}} + P_t^{c} - P_t^{d} - P_t^{g}$$

minimize energy from ES and generator
to balance critical load

subject to dynamics
constraints

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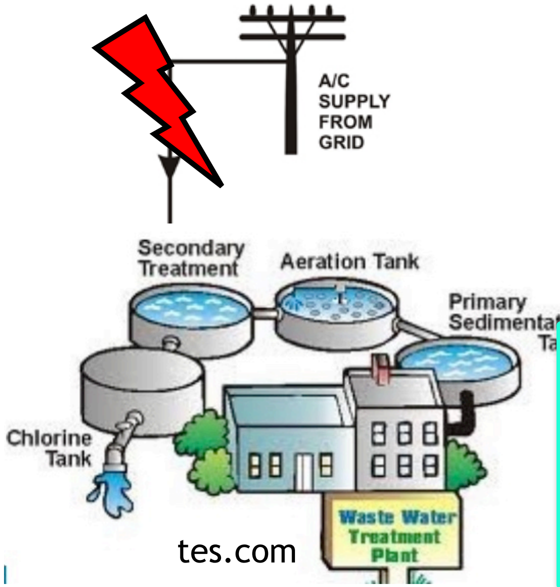

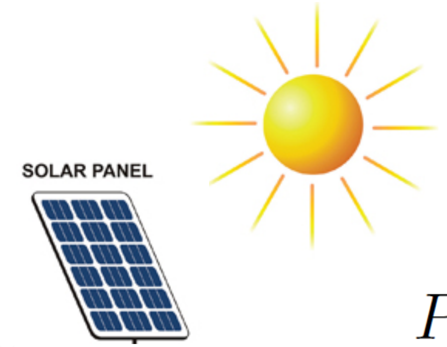

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Decision variables

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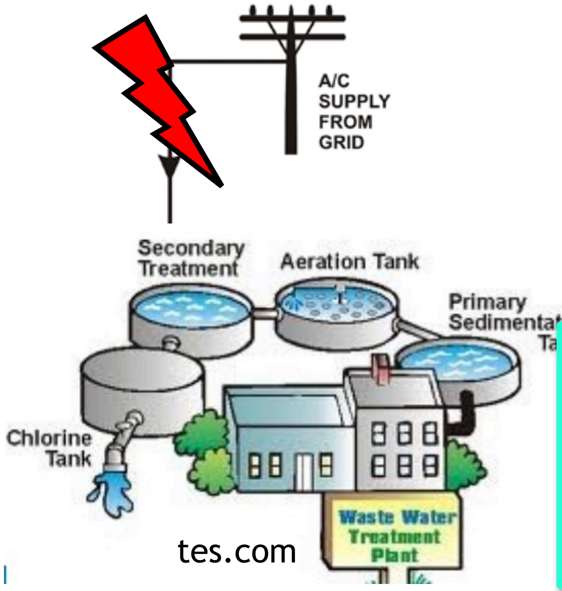

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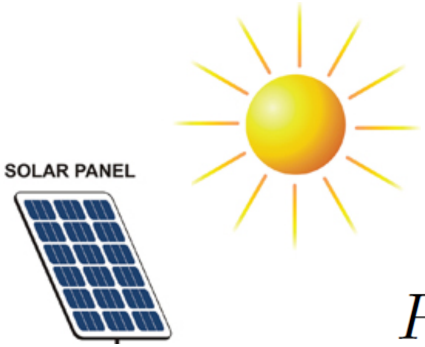

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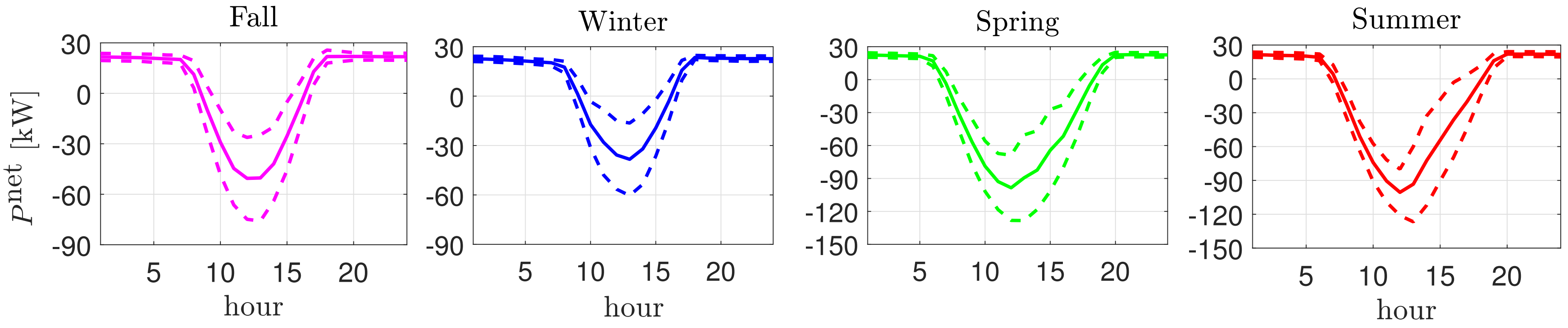

Copp, Nguyen, Byrne. *IEEE PESGM*, 2018.

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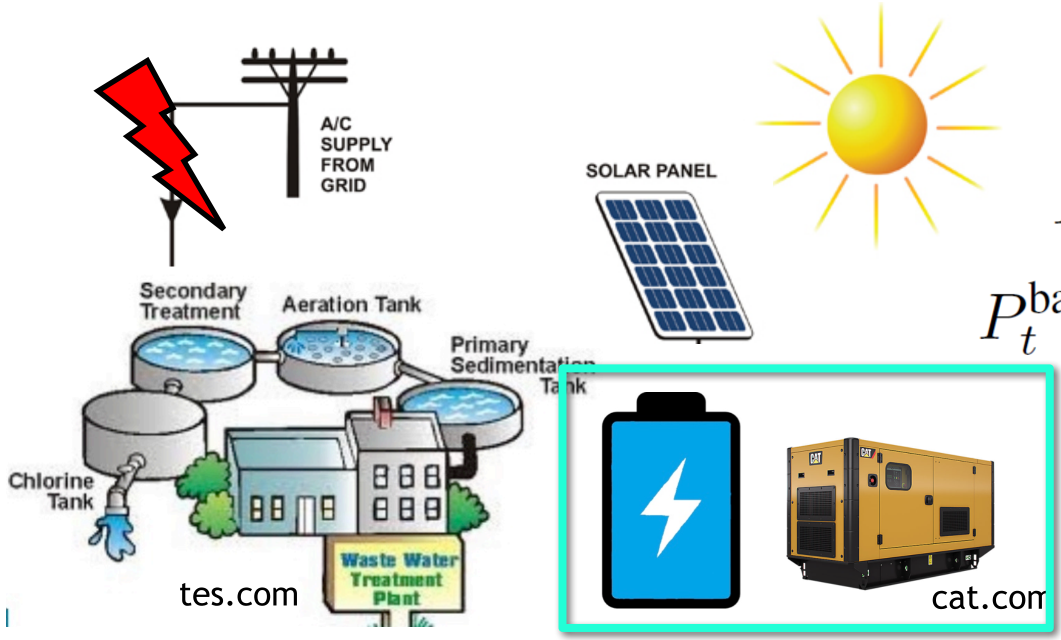

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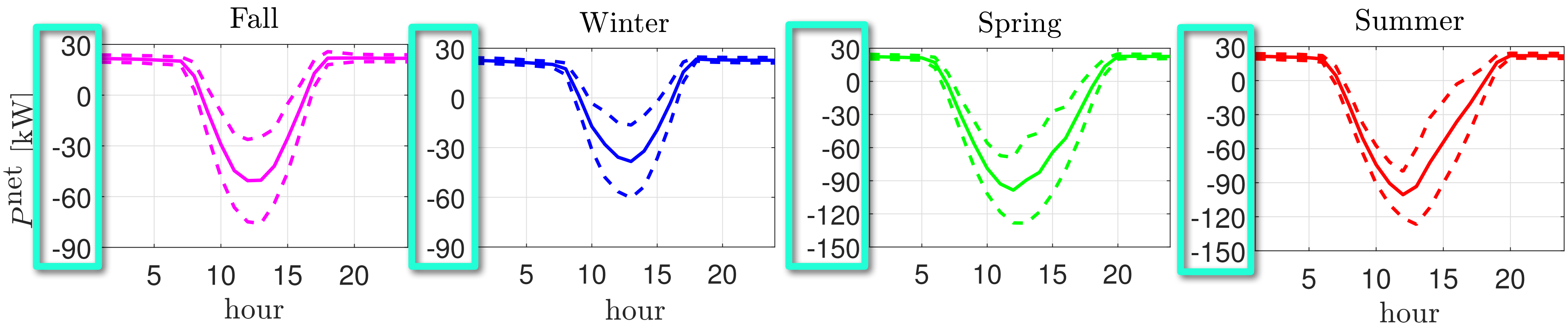

Copp, Nguyen, Byrne. *IEEE PESGM*, 2018.

# Stochastic Optimization

$$\min_{\mathbf{P}^c,\mathbf{P}^d,\mathbf{P}^g} \quad w_1\overline{S}_{\text{ESS}} + w_2\overline{S}_{\text{gen}} \qquad \forall t \in \mathcal{T}$$ Optimization horizon

subject to

$$\overline{S}_{\text{ESS}} \geq 0$$ ESS energy capacity

$$\sum_{t=1}^{T} P_t^g \leq \overline{S}_{\text{gen}}$$ Generator energy provided

$$P_t^c \geq 0$$ ESS charge

$$P_t^d \geq 0$$ ESS discharge

$$P_t^c + P_t^d \leq \overline{P}_{\text{ESS}}$$ ESS power rating

$$0 \leq P_t^g \leq \overline{P}_{\text{gen}}$$ Generator power rating

$$0 \leq \gamma_s S_t + \gamma_c P_t^c - P_t^d \leq \overline{S}_{\text{ESS}}$$ ESS SOC dynamics

$$\mathbb{P}\{P_t^{\text{net}} + P_t^c - P_t^d - P_t^g \leq 0\} \geq \alpha$$ Load balancing probabilistic constraint

**Copp, Nguyen, Byrne.** ***IEEE PESGM*****, 2018.**

# Stochastic Optimization

$$\min_{\mathbf{P}^c,\mathbf{P}^d,\mathbf{P}^g} \quad w_1\overline{S}_{\text{ESS}} + w_2\overline{S}_{\text{gen}} \qquad \forall t \in \mathcal{T}$$

Optimization horizon

subject to $\overline{S}_{\text{ESS}} \geq 0$ ESS energy capacity

If forecasts follow normal distributions…

→ probabilistic constraint can be formulated as a deterministic inequality constraint

Solve resulting Linear Program

$$0 \leq P_t^g \leq \overline{P}_{\text{gen}}$$

Generator power rating

$$0 \leq \gamma_s S_t + \gamma_c P_t^c - P_t^d \leq \overline{S}_{\text{ESS}}$$

ESS SOC dynamics

$$\mathbb{P}\{P_t^{\text{net}} + P_t^c - P_t^d - P_t^g \leq 0\} \geq \alpha$$

Load balancing probabilistic constraint

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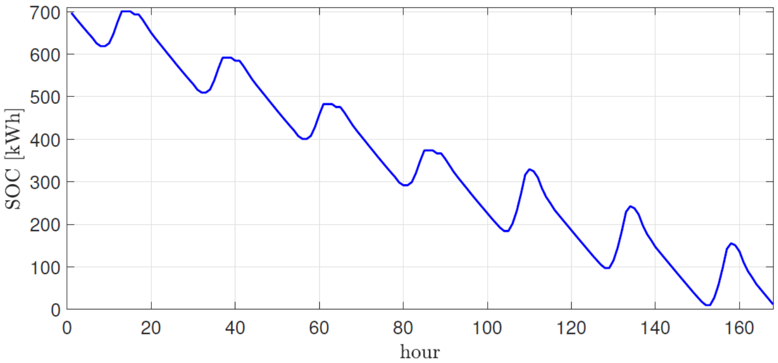
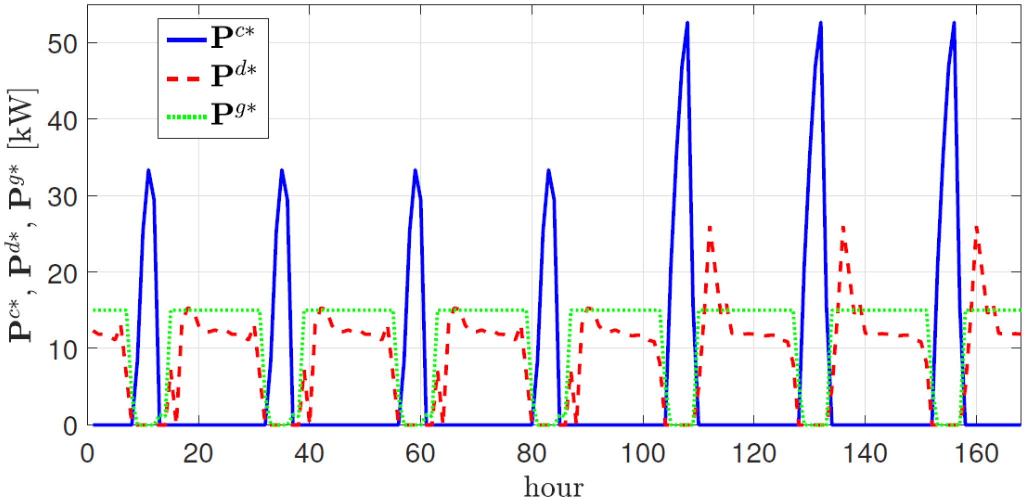
# Results: Optimizing Behind-the-Meter Energy Storage

$$\min_{\mathbf{P}^c,\mathbf{P}^d,\mathbf{P}^g} \quad w_1 \overline{S}_{\mathrm{ESS}} + w_2 \overline{S}_{\mathrm{gen}}$$

May 28 – June 3, 2016

| | |
|---|---|
| $\overline{S}^*_{\mathrm{ESS}}$ | 871 kWh |
| $\overline{S}^*_{\mathrm{gen}}$ | 1870 kWh |





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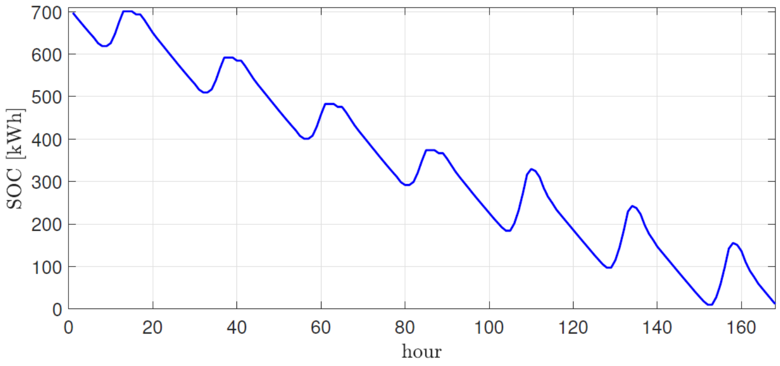

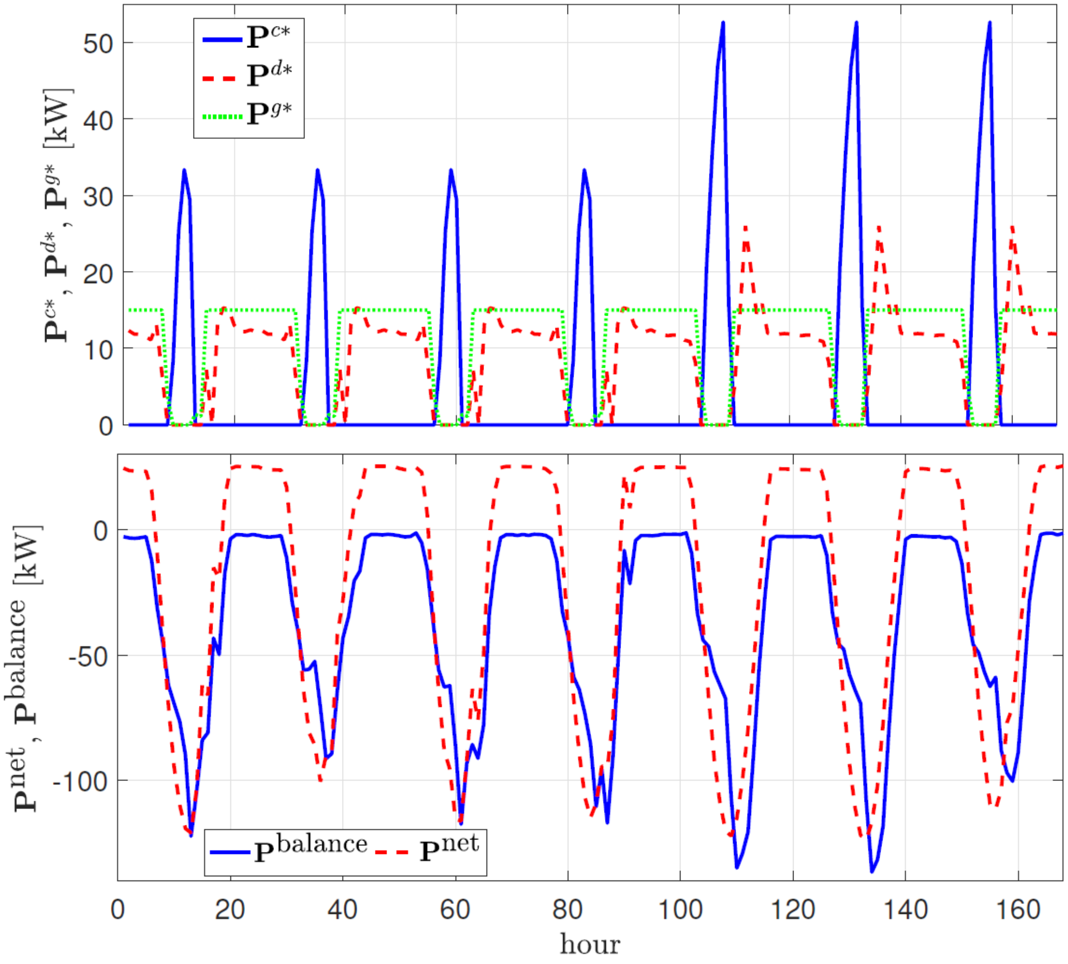

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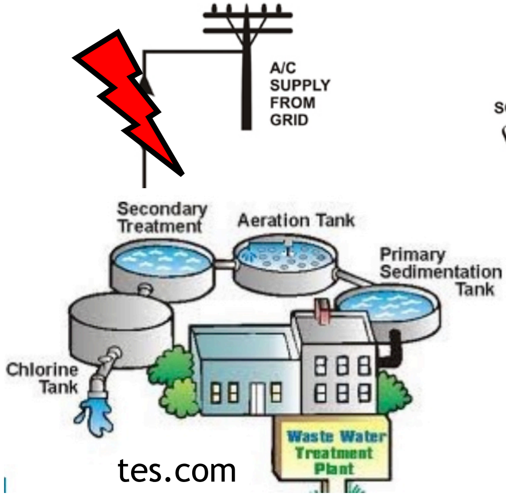
# Conclusion

- Proposed stochastic optimization for sizing and scheduling behind-the-meter energy storage.
- With normally distributed forecasting errors, probabilistic constraint can be reformulated as a linear inequality constraint, and optimization problem becomes a linear program.
- Case study: Reasonably-sized energy storage system, when optimally scheduled with the generator, successfully balanced critical load with *naive forecasts* of stochastic load and PV generation.
- Smaller energy storage may be used times of year when PV generation is higher relative to critical load, such as Spring and Summer.



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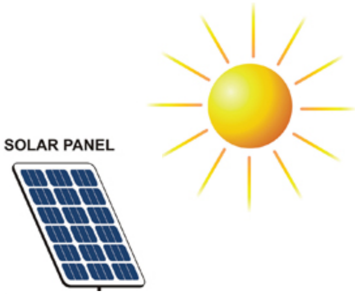

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# Acknowledgements

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Thank you.

# Extra slides

# Parameters

| Parameter | Description | Value | Units |
|---|---|---|---|
| $h$ | Time step | 1 | hour |
| $\gamma_{\text{PV}}$ | PV panel efficiency | 0.15 | - |
| $\gamma_{\text{conv}}$ | PV conversion efficiency | 0.90 | - |
| $\gamma_s$ | ESS storage efficiency | 1.00 | - |
| $\gamma_c$ | ESS charging efficiency | 0.85 | - |
| $A_{\text{PV}}$ | Total area of solar panels | 1000 | $\text{m}^2$ |
| $\overline{P}_{\text{ESS}}$ | ESS power rating | 150 | kW |
| $\overline{P}_{\text{gen}}$ | Generator power rating | 15 | kW |
| $S_0$ | Initial SOC | $0.8\overline{S}_{\text{ESS}}$ | kWh |
| $w_1$ | Weight on $\overline{S}_{\text{ESS}}$ | 1 | - |
| $w_2$ | Weight on $\overline{S}_{\text{gen}}$ | 1.1 | - |
| $T$ | Optimization horizon | 168 | hours |
| $\alpha$ | Desired fraction of time critical load is met | 0.99 | - |

| | May 28 - June 3 | August 28 - September 3 |
|---|---|---|
| $\overline{S}^*_{\text{ESS}}$ | 871 kWh | 1276 kWh |
| $\overline{S}^*_{\text{gen}}$ | 1870 kWh | 2092 kWh |

# Energy Storage Analytics

## Equitable Regulatory Environment Thrust Area

Goals: Lower barriers to widespread deployment of energy storage by identifying new and existing value streams, quantifying the impact of policy on deployment, and developing new control strategies

Objectives:

- Project case studies
- Tools for storage valuation
- Identify new value streams
- Control strategies to maximize revenue/grid benefit
- Assess policy impact on storage
- Develop policy recommendations

# Energy Storage as Flexible Resource

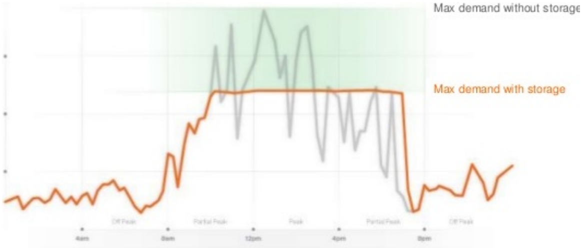
Grid-scale energy storage can enable significant cost savings to industry while improving infrastructure reliability and efficiency

Mitigate $79B/yr in commercial losses from outages

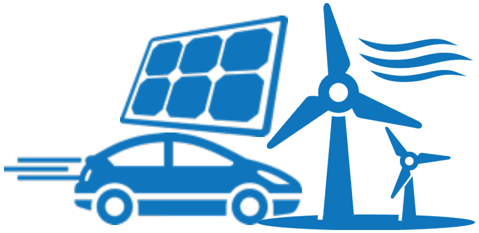
Regional Spending on T&D Projects Completed by 2020 Heavily Weighted Towards the Rockies

~66% of projected infrastructure spend through 2030 is distribution system upgrades

Reduce $2T in required T&D upgrades



Reduce commercial and industrial electrical bills through demand charge management. 7.5 million U.S. customers are enrolled in dynamic pricing (EIA 2015)



Balance the variability of 825 GW of new renewable generation while improving grid reliability and efficiency.

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