DOE/OE Transmission Reliability Program

DE-OE0000842
Multi-Stage and Multi-Timescale Robust Co-Optimization Planning for Reliable and Sustainable Power Systems

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Washington, DC

Outline

- **Overall Project Objective**
- **Looking Back (July 2017-June 2018)**
  - Major accomplishments
  - Deliverables and remaining schedule for activities to be completed under FY17 funding
  - A list of accepted publications
- **Looking Forward**
  - Outline planned activities and schedule

Overall Project Objective

- **Project Overview**
  - Period of Performance: October 1, 2016 – September 30, 2019
  - Program Manager: Phil Overholt
  - Project Officer: Alicia R. Dalton-Tingler
  - Principal Investigator: Lei Wu
  - Subrecipient
    - Bo Zeng, University of Pittsburgh
    - Jianhui Wang, Southern Methodist University
  - Industry Partners
    - ISO New England (ISO-NE)
    - Pennsylvania, Jersey, Maryland Power Pool (PJM)
    - Midcontinent Independent System Operator (MISO)
    - New York State Smart Grid Consortium

Overall Project Objective

- **Background**
  - o Long-term power system planning aims at optimizing asset utilization by investing in a proper mix of generation and transmission technologies/capacities to supply the future electrical load growth.
    - – Focus on environmental sustainability, energy reliability, and economic well-being over **multiple years**
    - – Mitigate risks and uncertainties of **multiple timescales**, from long-term policy/technology changes to short-term operation dynamics
    - – Coordinate long-term **reliability** and short-term **flexibility**
    - – Address **computational complexity** of practical-scale power systems, especially considering hourly operation details and nonlinear characteristics of the alternating current (AC) transmission network.

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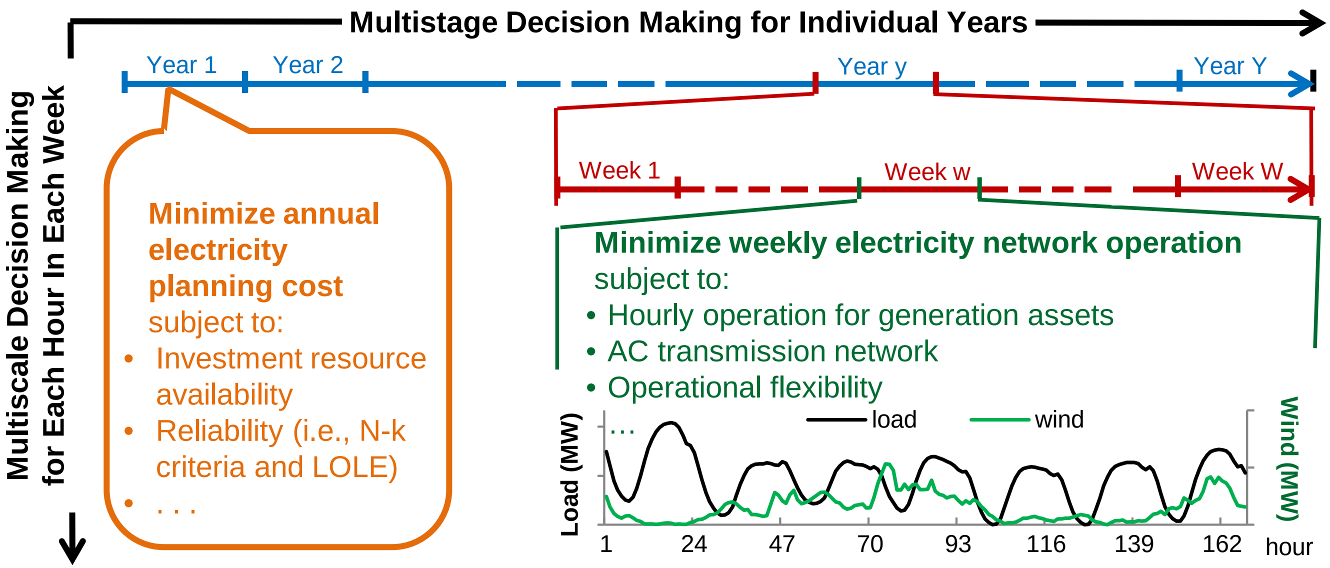
Overall Project Objective

- **Objective**
  - Develop **Multi-stage and Multi-timescale robust Co-Optimization Planning** to determine a proper mix of generation and transmission technologies/ capacities as well as novel non-wires alternatives for supplying the future electrical load growth.



Overall Project Objective

- **Modeling and Solution Approaches**
  - Advanced features for the modeling and simulation
    - Risks and uncertainties related to the time, location, and type of additional generation technologies
    - Annual, seasonal, and hourly variation of renewable energy sources
    - Integrated long-term reliable planning and short-term economic operation
    - AC transmission network
    - Various environmental considerations
  - Innovative solution methodologies
    - Dynamic transmission network reduction
    - Tighter convex approximation for AC power flow
    - Integrated decomposition approaches
    - Distributed computation methods

Look Back (July 2017-June 2018)

- **Major accomplishments during the past year**
  - Explored stochastic programming and robust optimization based joint generation and transmission planning model. The derived planning model can identify reliable co-optimization plans that are robust to critical randomness (uncertain loads, renewable energy, and policy/ technology changes) as well as generation and transmission contingencies.
  - Investigated a multi-area coordinated planning model which minimizes the investment costs and the worst-case costs for electricity production and unserved load over all areas.
  - Studied a set of approaches to effectively solve our co-optimization planning models, including a column-and-constraint-generation (CCG) algorithm and a state based model to evaluate impacts of operation decisions on the long-term planning horizon.

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Look Back (July 2017-June 2018)

- **Major accomplishments during the past year**
  - Some mathematical models and computational algorithms developed in this project have been integrated into graduate courses of collaborating universities
    - "*Computational Optimization*" in Fall 2017 at University of Pittsburgh. In Fall 2017, 6 graduate students enrolled in the course, from both engineering and business schools. This course is currently scheduled to be offered every other year.
    - "*Optimization Techniques in Engineering*" in Spring 2018 at Clarkson University. In Spring 2018, 5 undergraduate students and 11 graduate students enrolled in this class, from both engineering and business schools. This course is currently scheduled to be offered every other year.

Look Back (July 2017-June 2018)

- **Integrating DSR into Multi-Stage Robust Generation and Transmission Expansion Planning**
  - Optimize the investment in a proper mix of generators, transmission lines, and demand side resources (DSR) to supply future load growth.
  - Challenges to power system planning across multiple timescales
    - System expansions are **made over multiple stages** in a sequential fashion.
    - Renewable energy exhibits **multiple timescale variability**.
    - DSRs introduce additional **load fluctuations and forecast errors**.
  - The multi-stage planning horizon, the hourly operation details with uncertain factors, and the integration of long-term reliability and short-term flexibility must be simultaneously addressed.

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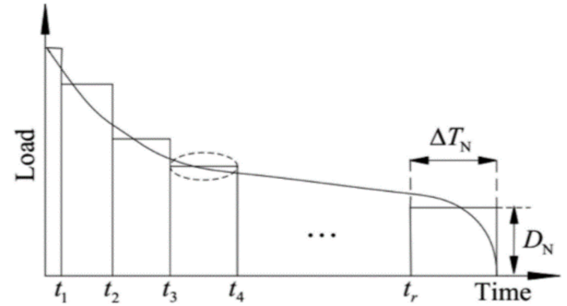
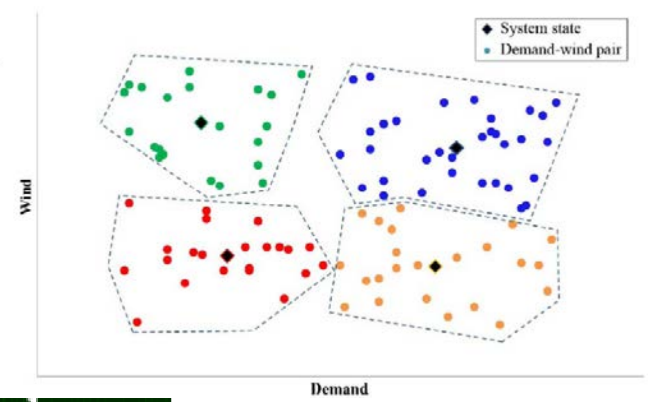
Look Back (July 2017-June 2018)

- **Integrating DSR into Multi-Stage Robust Generation and Transmission Expansion Planning**
  - Operation cost representation in long-term planning
    - Load duration curve



    - System state model
      - ✓ K-means clustering
      - ✓ Transition matrix



Look Back (July 2017-June 2018)

- **Integrating DSR into Multi-Stage Robust Generation and Transmission Expansion Planning**
  - Mathematical formulation

$$\min_{\boldsymbol{x}\in X}\left(Investment\_Cost(\boldsymbol{x}) + \max_{\boldsymbol{u}\in U}\ \min_{\boldsymbol{y},\boldsymbol{z}\in\Omega(\boldsymbol{x},\boldsymbol{u})} Operation\_Cost\,(\boldsymbol{y},\boldsymbol{z})\right)$$

$$\boldsymbol{X} = \left\{\boldsymbol{x}\colon \begin{array}{lll} x_{g,t}, x_{l,t}, x_{d,t} \in \{0,1\}, & g \in G^c, l \in L^c, d \in D^c \\ x_{g,t-1} \le x_{g,t}, & x_{l,t-1} \le x_{l,t}, & x_{d,t-1} \le x_{d,t} \end{array}\right\}$$

$$\boldsymbol{U} = \left\{\boldsymbol{u}\colon \begin{array}{c} P^u_{d,t,s} \in \mathbb{R}^{NT\times NS}, P^u_{w,t,s} \in \mathbb{R}^{NT\times NS} \\ P^u_{d,t,s} = P_{d,t,s} + \delta^+_{d,t,s}\cdot\tilde{P}^+_{d,t,s} + \delta^-_{d,t,s}\cdot\tilde{P}^-_{d,t,s}; \sum_{t,s}(\delta^+_{d,t,s}+\delta^-_{d,t,s}) \le \Delta_d, \delta^+_{d,t,s}+\delta^-_{d,t,s} \le 1 \\ P^u_{w,t,s} = P_{w,t,s} + \delta^+_{w,t,s}\cdot\tilde{P}^+_{w,t,s} + \delta^-_{w,t,s}\cdot\tilde{P}^-_{w,t,s}; \sum_{t,s}(\delta^+_{w,t,s}+\delta^-_{w,t,s}) \le \Delta_w, \delta^+_{w,t,s}+\delta^-_{w,t,s} \le 1 \end{array}\right\}$$

$$\Omega(\boldsymbol{x},\boldsymbol{u}) = \left\{\begin{array}{c} P^{min}_g \cdot y_{g,t,s}\cdot x_{g,t} \le p_{g,t,s} \le P^{max}_g \cdot y_{g,t,s}\cdot x_{g,t} \\ 0 \le dr_{d,t,s} \le DR^{max}_{d,t}\cdot x_{d,t}\cdot y_{d,t,s} \\ -P^{max}_l \cdot x_{l,t} \le p_{l,t,s} \le P^{max}_l \cdot x_{l,t} \\ -M\cdot(1-x_{l,t}) \le B_l\cdot\left(\theta_{s(l),t,s} - \theta_{r(l),t,s}\right) - p_{l,t,s} \le M\cdot(1-x_{l,t}) \\ \sum_{g\in B_g(i)} p_{g,t,s} + \sum_{l\in R(i)} p_{l,t,s} - \sum_{l\in S(i)} p_{l,t,s} + \sum_{w\in B_w(i)} p_{w,t,s} + v_{i,t,s} = \sum_{d\in B_d(i)} \left(P^u_{d,t,s} - dr_{d,t,s}\right) \end{array}\right\}$$

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Look Back (July 2017-June 2018)

- **Integrating DSR into Multi-Stage Robust Generation and Transmission Expansion Planning**
  - Approximate column-and-constraint generation based decomposition

$$\min_{\boldsymbol{x},\eta} \; IC(\boldsymbol{x}) + \eta$$

s.t.

$$\boldsymbol{x} \in \boldsymbol{X};\; \boldsymbol{y}^r, \boldsymbol{z}^r \in \; \Omega(\boldsymbol{x}, \boldsymbol{u}^r)$$

$$\eta \geq \; OC(\boldsymbol{y}^r, \boldsymbol{z}^r)$$

$$\boldsymbol{y}^r \in \{0,1\}, \quad \boldsymbol{z}^r \geq \boldsymbol{0}$$

$\boldsymbol{u}^0$

$$V(\boldsymbol{x}^*) = \max_{\boldsymbol{u}\in \boldsymbol{U}} \min_{\boldsymbol{y},\boldsymbol{z}\in\Omega(\boldsymbol{x}^*,\boldsymbol{u})} OC\,(\boldsymbol{y}^*, \boldsymbol{z})$$

$\boldsymbol{LB = IC(x^r) + \eta^r}$

$\boldsymbol{UB = \min\{UB, IC(x^r) + \widetilde{V}(x^r)\}}$

$\boldsymbol{y}^*$

$$V(\boldsymbol{x}^*) = \max_{\boldsymbol{u}\in \boldsymbol{U}} \min_{\boldsymbol{y},\boldsymbol{z}\in\Omega(\boldsymbol{x}^*,\boldsymbol{u})} OC\,(\boldsymbol{y}, \boldsymbol{z})$$

$$\boldsymbol{y} \in [0,1]$$

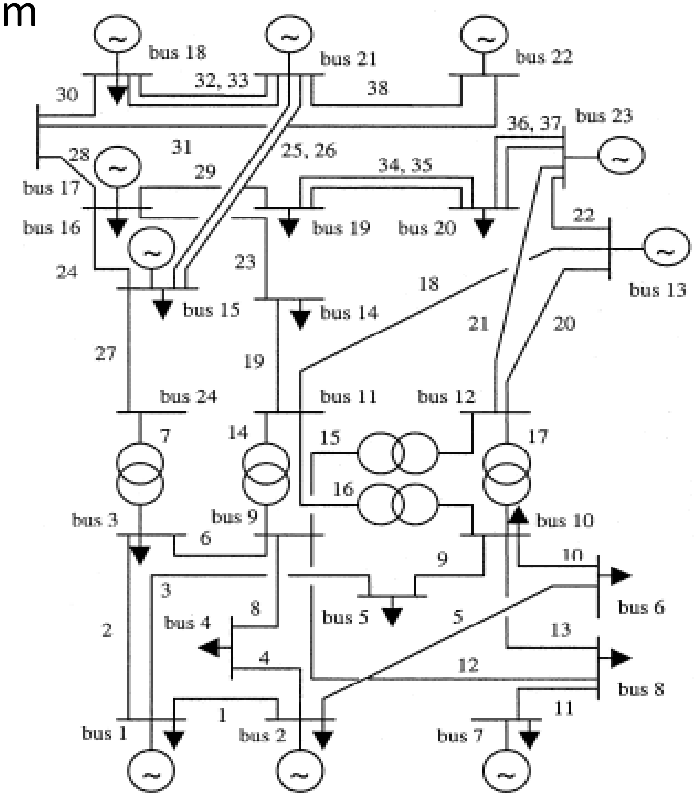
$\boldsymbol{u}^*$

$$\min_{\boldsymbol{y},\boldsymbol{z}\in\Omega(\boldsymbol{x}^*,\boldsymbol{u}^*)} OC\,(\boldsymbol{y}, \boldsymbol{z})$$

$$\boldsymbol{y} \in \{0,1\}$$

Look Back (July 2017-June 2018)

- **Integrating DSR into Multi-Stage Robust Generation and Transmission Expansion Planning**
  - Case Studies via the IEEE RTS-96 test system
    - o 10 Candidate Units
    - o 8 Candidate lines
    - o 10 Candidate DSRs



Look Back (July 2017-June 2018)

- **Integrating DSR into Multi-Stage Robust Generation and Transmission Expansion Planning**
  - Case Studies via the IEEE RTS-96 test system
    - Impact of different DSR participation levels

Participation levels	TC (10^{10}\$)	IC (10^{9}\$)	Gen Inv. Decision	Trans Inv. Decision
Low	3.0795	3.426	$G_{3,1}G_{4,3}G_{7,3}G_{8,10}$	$T_{1,2}T_{2,1}T_{3,1}T_{4,1}T_{5,10}T_{7,1}T_{8,1}$
Medium	2.990	3.784	$G_{3,1}G_{4,4}G_{7,3}G_{8,10}$	$T_{1,2}T_{2,1}T_{3,1}T_{4,1}T_{5,8}T_{7,1}T_{8,1}$
High	2.905	3.545	$G_{3,1}G_{4,4}G_{7,4}G_{8,10}$	$T_{1,4}T_{2,1}T_{3,1}T_{4,1}T_{5,9}T_{7,1}T_{8,1}$

Look Back (July 2017-June 2018)

- **Integrating DSR into Multi-Stage Robust Generation and Transmission Expansion Planning**
  - Case Studies via the IEEE RTS-96 test system
    - Impact of different DSR participation levels
    - Impact of different DSR investment costs (IC)

DSR IC	TC (10^{10}\$)	IC (10^{9}\$)	Gen Inv. Decision	Trans Inv. Decision
Low	2.985	$G_{3,1}G_{4,4}G_{7,3}G_{8,10}$	$T_{1,3}T_{2,1}T_{3,1}T_{4,1}$ $T_{5,8}T_{7,1}T_{8,1}$	$D_{1,1}D_{2,2}D_{3,1}D_{4,1}D_{5,1}$ $D_{6,1}D_{7,1}D_{8,1}D_{9,1}D_{10,1}$
Medium	2.99	$G_{3,1}G_{4,4}G_{7,3}G_{8,10}$	$T_{1,2}T_{2,1}T_{3,1}T_{4,1}$ $T_{5,8}T_{7,1}T_{8,1}$	$D_{1,1}\mathbf{D_{2,8}}D_{3,1}D_{4,1}D_{5,1}$ $D_{6,1}D_{7,1}D_{8,1}D_{9,1}D_{10,1}$
High	3.00	$G_{3,1}G_{4,4}G_{7,3}G_{8,10}$	$T_{1,3}T_{2,1}T_{3,1}T_{4,1}$ $T_{5,10}T_{7,1}T_{8,1}$	$\mathbf{D_{1,10}}D_{3,1}D_{4,1}D_{5,1}$ $D_{6,1}\mathbf{D_{7,6}}D_{8,1}D_{9,1}D_{10,1}$

Look Back (July 2017-June 2018)

- **Integrating DSR into Multi-Stage Robust Generation and Transmission Expansion Planning**
  - Case Studies via the IEEE RTS-96 test system
    - Impact of different DSR participation levels
    - Impact of different DSR investment costs (IC)
    - Impact of different uncertainty levels

Uncertainty Level	TC (10^{10}\$)	Gen inv. decision	Trans Inv. decision	DSRs Inv. decision
0	2.203	$G_{3,1}G_{4,5}G_{7,4}$	$T_{1,5}T_{2,1}T_{3,1}$ $T_{4,1}T_{7,1}T_{8,1}$	$D_{1,1}D_{3,1}D_{4,1}D_{5,1}D_{6,1}$ $D_{7,1}D_{8,1}D_{9,1}D_{10,1}$
0.25	2.642	$G_{3,1}G_{4,4}G_{7,4}$	$\mathbf{T_{1,4}}T_{2,1}T_{3,1}$ $T_{4,1}T_{7,1}T_{8,1}$	$\mathbf{D_{1,3}D_{2,8}}D_{3,1}D_{4,1}D_{5,1}$ $D_{6,1}D_{7,1}D_{8,1}D_{9,1}D_{10,1}$
0.5	2.7998	$G_{3,1}G_{4,4}G_{7,4}\mathbf{G_{8,10}}$	$\mathbf{T_{1,3}}T_{2,1}T_{3,1}T_{4,1}$ $\mathbf{T_{5,10}}T_{7,1}T_{8,1}$	$\mathbf{D_{1,2}D_{2,8}}D_{3,1}D_{4,1}D_{5,1}$ $D_{6,1}D_{7,4}D_{8,1}D_{9,1}D_{10,1}$
0.75	2.933	$G_{3,1}G_{4,4}\mathbf{G_{7,3}G_{8,10}}$	$\mathbf{T_{1,4}}T_{2,1}T_{3,1}T_{4,1}$ $\mathbf{T_{5,8}}T_{7,1}T_{8,1}$	$\mathbf{D_{1,2}D_{2,8}}D_{3,1}D_{4,1}D_{5,1}$ $D_{6,1}D_{7,1}D_{8,1}D_{9,1}D_{10,1}$
1	2.99	$G_{3,1}G_{4,4}\mathbf{G_{7,3}G_{8,10}}$	$\mathbf{T_{1,2}}T_{2,1}T_{3,1}T_{4,1}$ $\mathbf{T_{5,8}}T_{7,1}T_{8,1}$	$\mathbf{D_{1,1}D_{2,8}}D_{3,1}D_{4,1}D_{5,1}$ $D_{6,1}D_{7,1}D_{8,1}D_{9,1}D_{10,1}$

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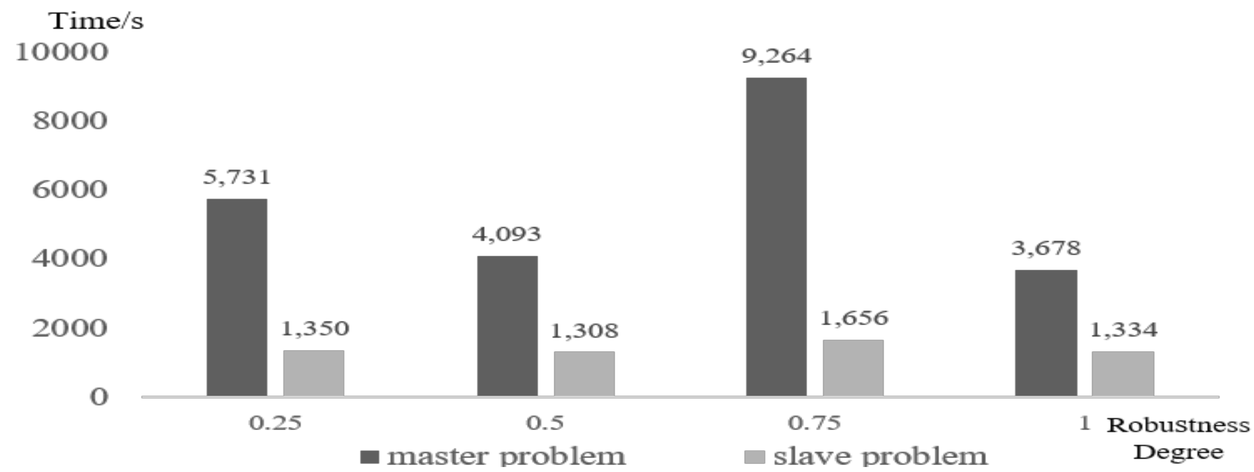
Look Back (July 2017-June 2018)

- **Integrating DSR into Multi-Stage Robust Generation and Transmission Expansion Planning**
  - Case Studies via the IEEE RTS-96 test system
    - Impact of different DSR participation levels
    - Impact of different DSR investment costs (IC)
    - Impact of different uncertainty levels
    - Computational performance



Look Back (July 2017-June 2018)

- **Deliverables and remaining schedule for activities to be completed under FY17 funding**
  - The team will implement the proposed model and algorithms through a high-level modeling system with linkages to many nonlinear and mixed-integer solvers. – June 30th 2018.
  - Annual Two Deliverables: programmatic metrics, publications, and presentations. – September 30th 2018.

Look Back (July 2017-June 2018)

- **A list of accepted publications and presentations**
  - [J4] X. Cao, J. Wang, and **B. Zeng**, "A Chance Constrained Information-Gap Decision Model for Multi-Period Microgrid Planning," in *IEEE Transactions on Power Systems*, vol. 33, no. 3, pp. 2684-2695, May 2018.
  - [J3] C. He, **L. Wu**, T. Liu, and Z. Bie, "Robust Co-Optimization Planning of Interdependent Electricity and Natural Gas Systems With a Joint N-1 and Probabilistic Reliability Criterion," *IEEE Transactions on Power Systems*, vol. 33, no. 2, pp. 2140-2154, Mar. 2018.
  - [J2] Y. Wang, **L. Wu**, and J. Li, "A Fully-Distributed Asynchronous Approach for Multi-Area Coordinated Network-Constrained Unit Commitment," *Optimization and Engineering*, pp. 1-34, DOI: https://doi.org/10.1007/ s11081-018-9375-8, Feb. 2018.
  - [J1] A. Bagheri, **J. Wang**, and C. Zhao, "Data-Driven Stochastic Transmission Expansion Planning," *IEEE Transactions on Power Systems*, vol. 32, no. 5, pp. 3461-3470, Sept. 2017.
  - [P2] **B. Zeng**, "A Study on Generalized Security Games in Power Systems," in *2018 INFORMS Optimization Conference*, Denver, CO, Mar. 23-25, 2018.
  - [P1] **L. Wu** and **B. Zeng**, "Multi-Stage and Multi-Timescale Robust Co-Optimization Planning for Reliable and Sustainable Power Systems," *INFORMS Annual Meeting*, Houston, TX , Oct. 19, 2017.

Looking Forward (July 2018- June 2019)

- **Planned activities and schedule for July 2018- June 2019**
  - Verify the effectiveness of the developed approaches via standard testing systems. The impacts on annual planning and hourly operation, long-term reliability and short-term flexibility, AC power flows, as well as risk and uncertainty accommodations will be analyzed. – November 2018
  - Test the MMCOP framework and algorithms via practical system expansion planning dataset to further illustrate the performance of the proposed enhanced solution methodologies in terms of the computational time and solution optimality. – June 2019
  - Approach industrial partners to customize the models and computational tools according to their specifications and needs, and provide technical support to promote co-optimization in their system expansion planning. – June 2019
  - Continue to develop curriculum and offer a graduate courses based on the work performed during this project. – June 2019

Thank you!

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