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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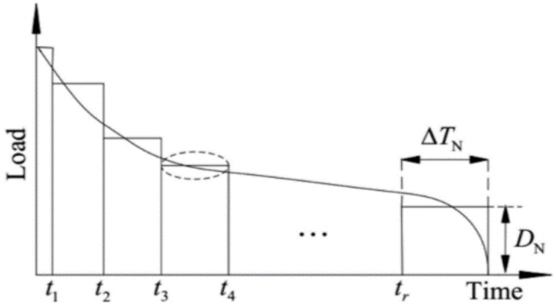
Washington, DC

Outline

- **Overall Project Objective**
- **Looking Back (July 2018-June 2019)**
  - Major accomplishments
  - Deliverables and remaining schedule for activities to be completed under FY18 funding
  - A list of accepted publications
- **Looking Forward**
  - Outline planned activities and schedule

Overall Project Objective

- **Background**
  - 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.
    - Traditional long-term planning approaches mainly focus on system **reliability** in terms of enough capacity investment for supplying future loads.
      - Peak load
      - Load duration curve



    - Long-term planning of emerging power systems also needs to ensure enough system **flexibility** for handling variabilities and uncertainties such as those from renewables.

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 (such as demand side resources) for supplying the future electrical load growth.
    - Focus on **co-optimizing** generation, transmission, and other non-wires alternatives to ensure environmental sustainability, energy reliability, and economic well-being over **multiple years**
    - Coordinate long-term **reliability** and short-term **flexibility**
    - Mitigate risks and uncertainties of **multiple timescales**, from long-term policy/technology changes to short-term operation dynamics
    - Address **computational complexity** of practical-scale power systems.

Look Back (July 2018-June 2019)

- **Major accomplishments during the past year**
  - Explored stochastic programming and robust optimization based joint generation, transmission, and demand side resource 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.
  - 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.

Look Back (July 2018-June 2019)

- **Integrating Demand Side Resources into Multi-Stage Robust Generation and Transmission Expansion Planning**
  - Minimizes (investment costs of generators, transmission lines, and demand side resources to supply future load growth) + (worst-case costs for electricity production and unserved load)

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

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

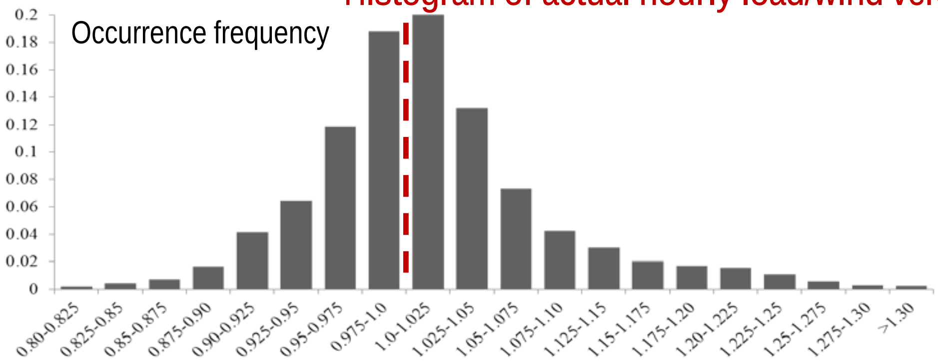
$$\boldsymbol{U} = \left\{\boldsymbol{u}\colon \begin{array}{c} P^u_{d,t,s} \in \mathbb{R}^{NT\times NS}, P^u_{w,t,s} \in \mathbb{R}^{NT\times NS} \\ P^u_{d,t,s} = P_{d,t,s} + \delta^+_{d,t,s}\cdot\tilde{P}^+_{d,t,s} + \delta^-_{d,t,s}\cdot\tilde{P}^-_{d,t,s}; \sum_{t,s}(\delta^+_{d,t,s} + \delta^-_{d,t,s})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

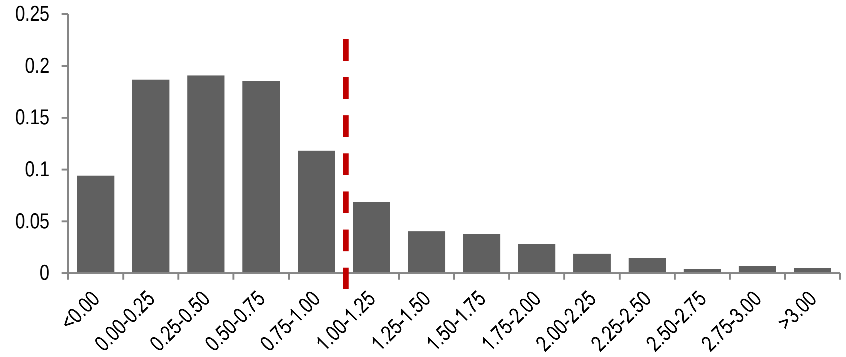
$$\Omega(\boldsymbol{x},\boldsymbol{u}) = \left\{\begin{array}{c} P^{min}_g \cdot y_{g,t,s}\cdot x_{g,t} \le p_{g,t,s} \le P^{max}_g \cdot y_{g,t,s}\cdot x_{g,t} \\ 0 \le dr_{d,t,s} \le DR^{max}_{d,t}\cdot x_{d,t}\cdot y_{d,t,s} \\ -P^{max}_l \cdot x_{l,t} \le p_{l,t,s} \le P^{max}_l \cdot x_{l,t} \\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

Look Back (July 2018-June 2019)

- **Modeling and Solution Approaches**
  - Features of the proposed modeling and simulation
    - Risks and uncertainties related to the time, location, and type of additional generation technologies (renewable energy sources in particular)

Histogram of actual hourly load/wind versus load/wind forecast in NYISO





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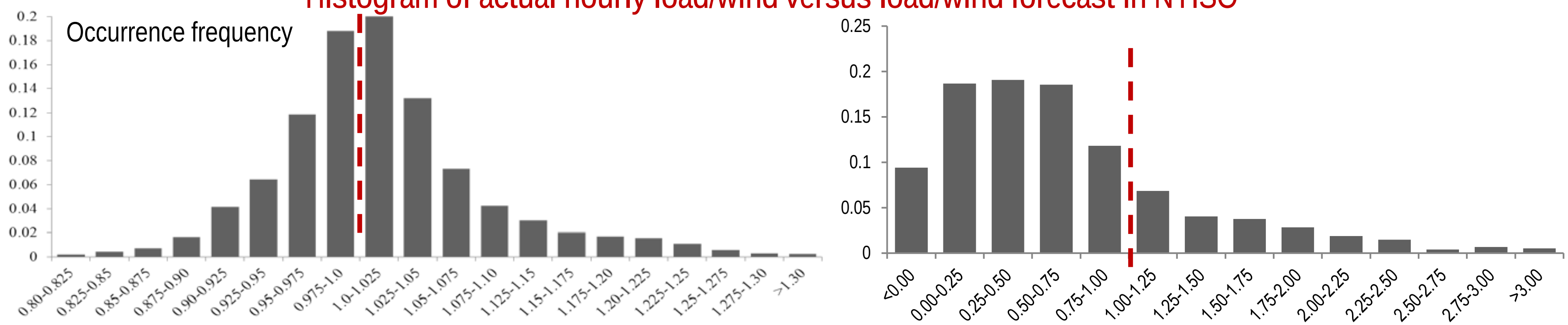

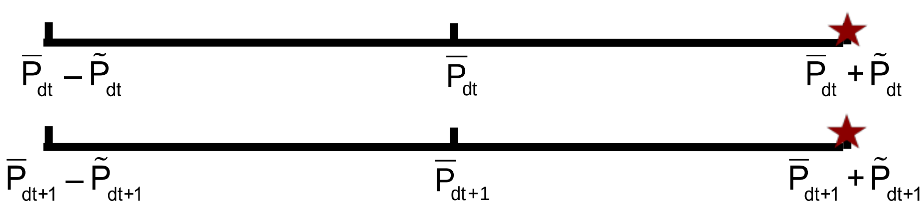

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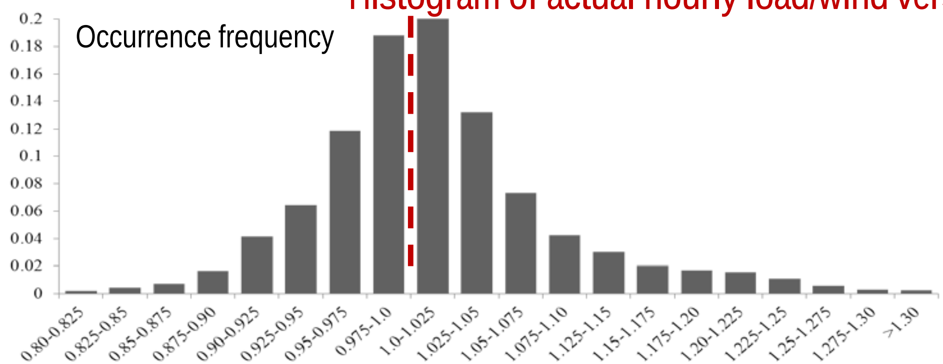

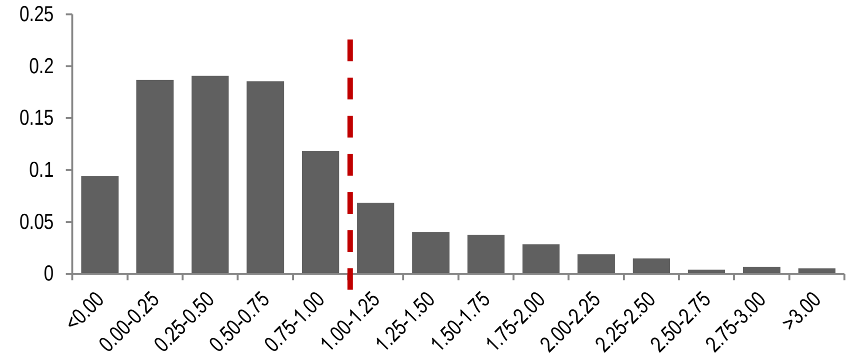

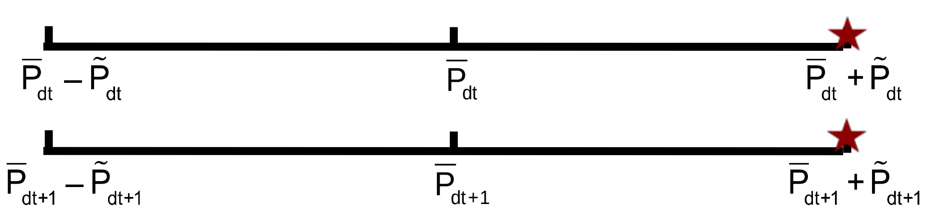

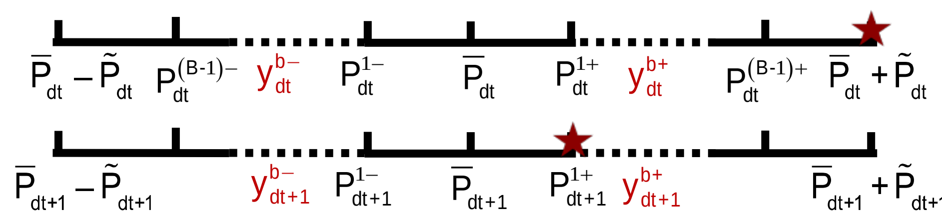

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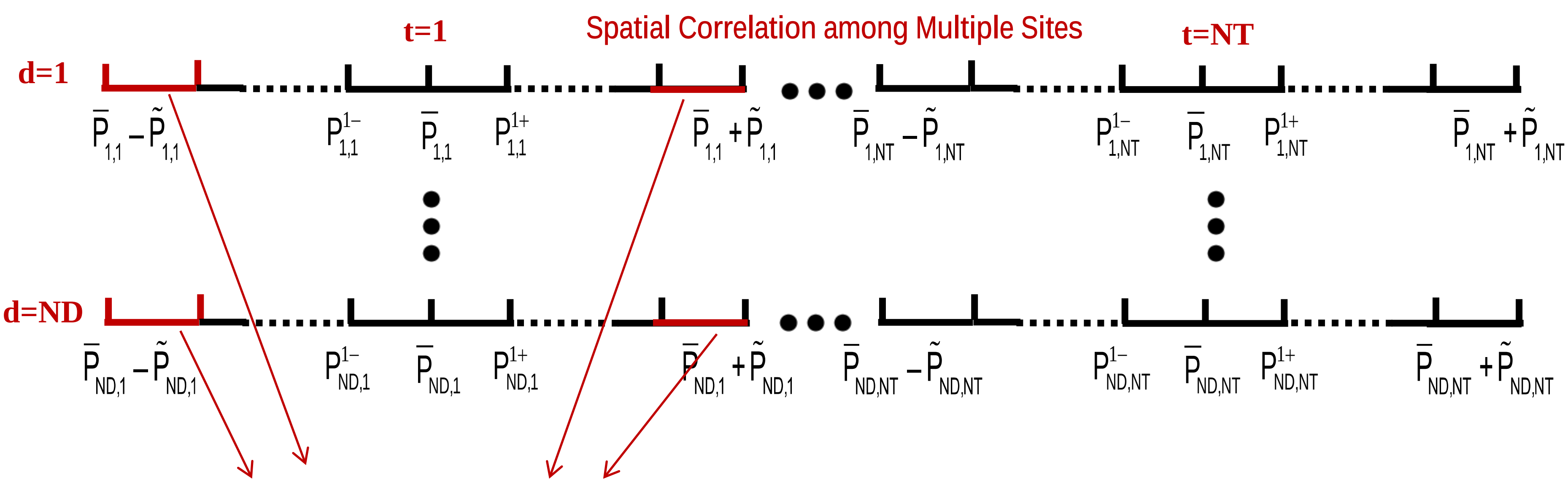

$$\sum_{d} (y_{dt}^{b+} + y_{dt}^{b-}) \le \left\lceil \pi_t^b \cdot \Delta_{d1} \right\rceil; \qquad \forall b, \forall t$$

Look Back (July 2018-June 2019)

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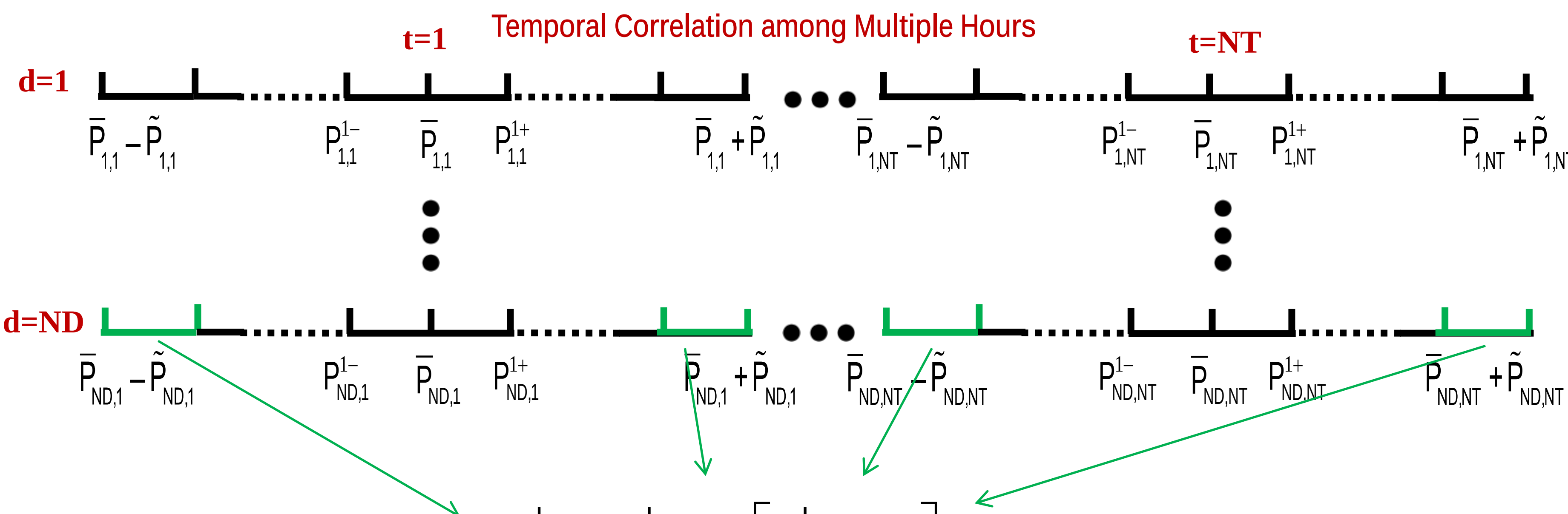
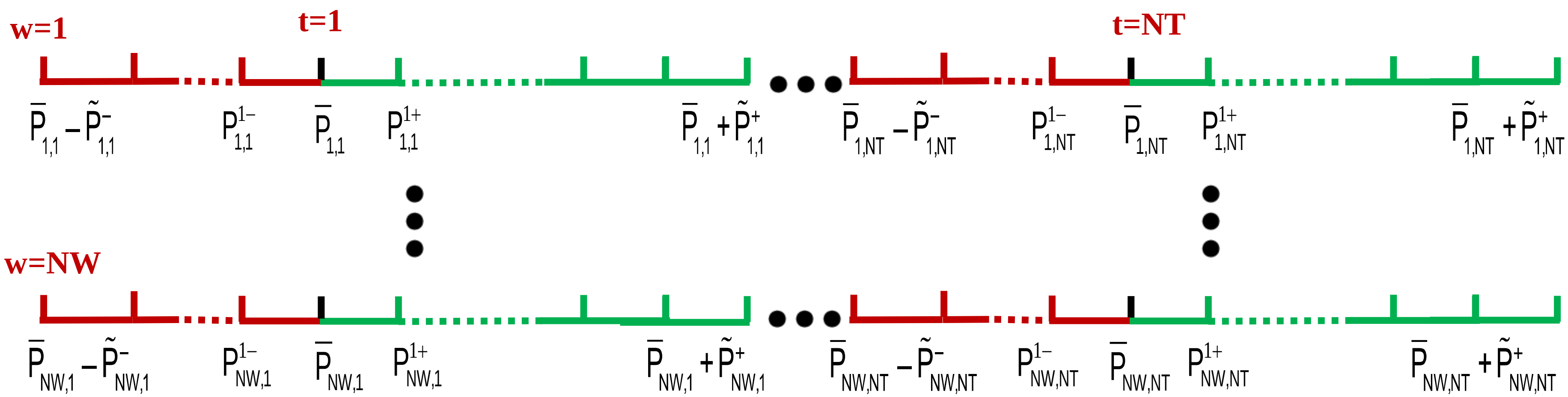


$$\sum_t (y^{b+}_{dt} + y^{b-}_{dt}) \leq \left\lceil \pi^b_d \cdot \Delta_{d2} \right\rceil; \qquad \forall b, \forall d$$

Look Back (July 2018-June 2019)

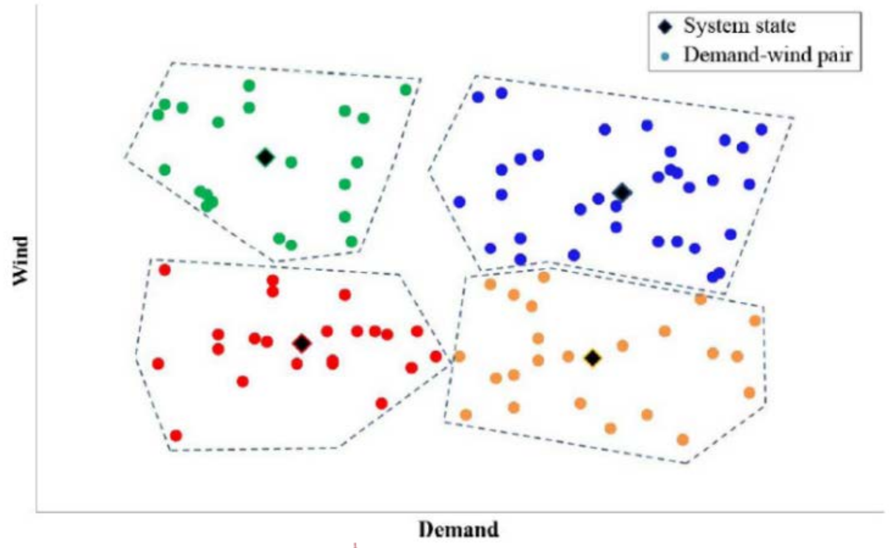
- **Modeling and Solution Approaches**
  - o Features of the proposed modeling and simulation
    - – Risks and uncertainties related to the time, location, and type of additional generation technologies (renewable energy sources in particular)



$$\sum_{t}\sum_{w}\sum_{b} y_{wt}^{b-} \le \left\lceil \pi^{-} \cdot \Delta_{w} \right\rceil; \qquad \sum_{t}\sum_{w}\sum_{b} y_{wt}^{b+} \le \left\lceil \pi^{+} \cdot \Delta_{w} \right\rceil$$

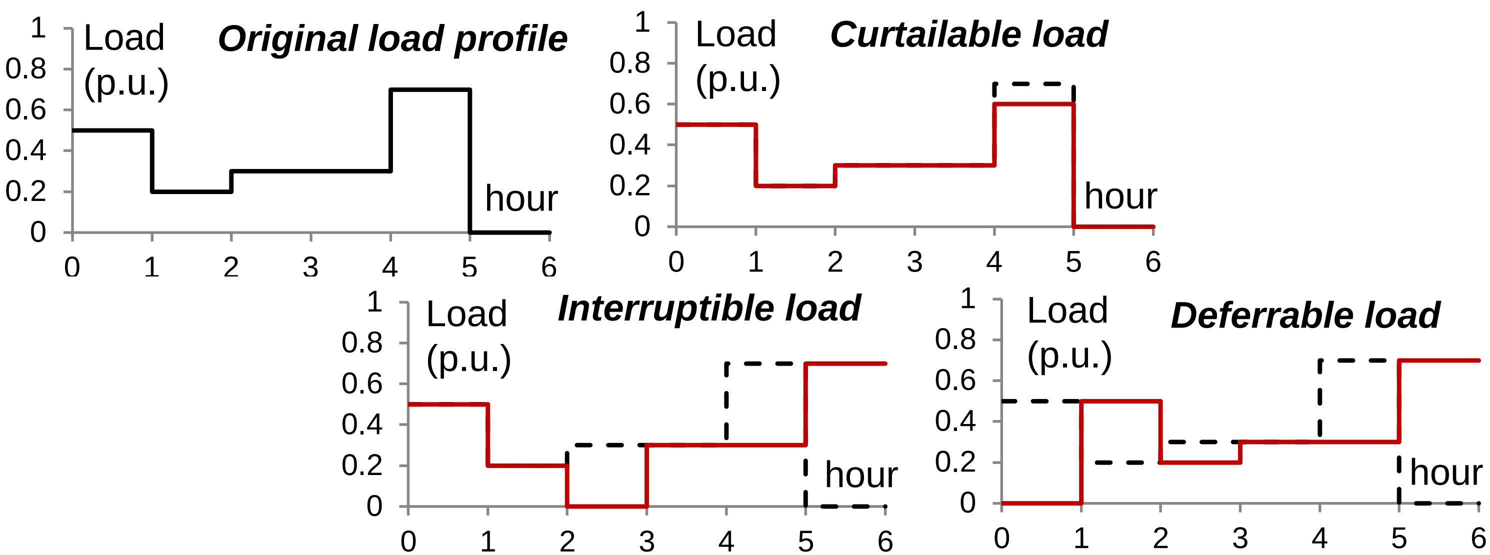
Look Back (July 2018-June 2019)

- **Modeling and Solution Approaches**
  - Features of the proposed modeling and simulation
    - Integrated long-term reliable planning and short-term economic operation
      - System state model
        - ✓ K-means clustering
        - ✓ Transition matrix



Look Back (July 2018-June 2019)

- **Modeling and Solution Approaches**
  - o Features of the proposed modeling and simulation
    - – Modeling on distinct spatial and temporal operation characteristics of various demand side resources in the operation stage, in order to accurately evaluate their benefits and impacts on power system planning



Look Back (July 2018-June 2019)

- **Modeling and Solution Approaches**
  - Approximate column-and-constraint generation based decomposition

$$\begin{aligned} \min_{\boldsymbol{x},\eta} \quad & IC(\boldsymbol{x}) + \eta \\ \text{s.t.} \quad & \boldsymbol{x} \in \boldsymbol{X};\ \boldsymbol{y}^r, \boldsymbol{z}^r \in \Omega(\boldsymbol{x}, \boldsymbol{u}^r) \\ & \eta \geq OC(\boldsymbol{y}^r, \boldsymbol{z}^r) \\ & \boldsymbol{y}^r \in \{0,1\}, \quad \boldsymbol{z}^r \geq \boldsymbol{0} \end{aligned}$$

$\boldsymbol{u}^0$

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

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

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

$\boldsymbol{y}^*$

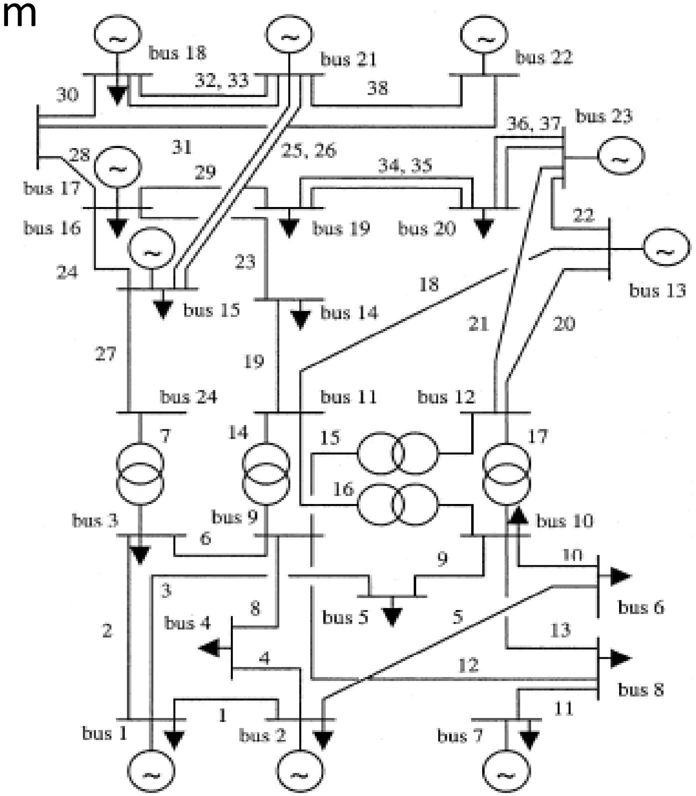
$$V(\boldsymbol{x}^*) = \max_{\boldsymbol{u}\in \boldsymbol{U}} \min_{\boldsymbol{y},\boldsymbol{z}\in\Omega(\boldsymbol{x}^*,\boldsymbol{u})} OC(\boldsymbol{y}, \boldsymbol{z}), \quad \boldsymbol{y} \in [0,1]$$

$\boldsymbol{u}^*$

$$\min_{\boldsymbol{y},\boldsymbol{z}\in\Omega(\boldsymbol{x}^*,\boldsymbol{u}^*)} OC(\boldsymbol{y}, \boldsymbol{z}), \quad \boldsymbol{y} \in \{0,1\}$$

Look Back (July 2018-June 2019)

- **Integrating Demand Side Resources 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 Demand Side Resources



Look Back (July 2018-June 2019)

- **Integrating Demand Side Resources into Multi-Stage Robust Generation and Transmission Expansion Planning**
  - Case Studies via the IEEE RTS-96 test system
    - Impact of different participation levels of demand side resources

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 2018-June 2019)

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

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	$G_{3,1}G_{4,4}G_{7,3}G_{8,10}$	$T_{1,3}T_{2,1}T_{3,1}T_{4,1}$ $T_{5,10}T_{7,1}T_{8,1}$	$\mathbf{D_{1,10}}D_{3,1}D_{4,1}D_{5,1}$ $D_{6,1}\mathbf{D_{7,6}}D_{8,1}D_{9,1}D_{10,1}$

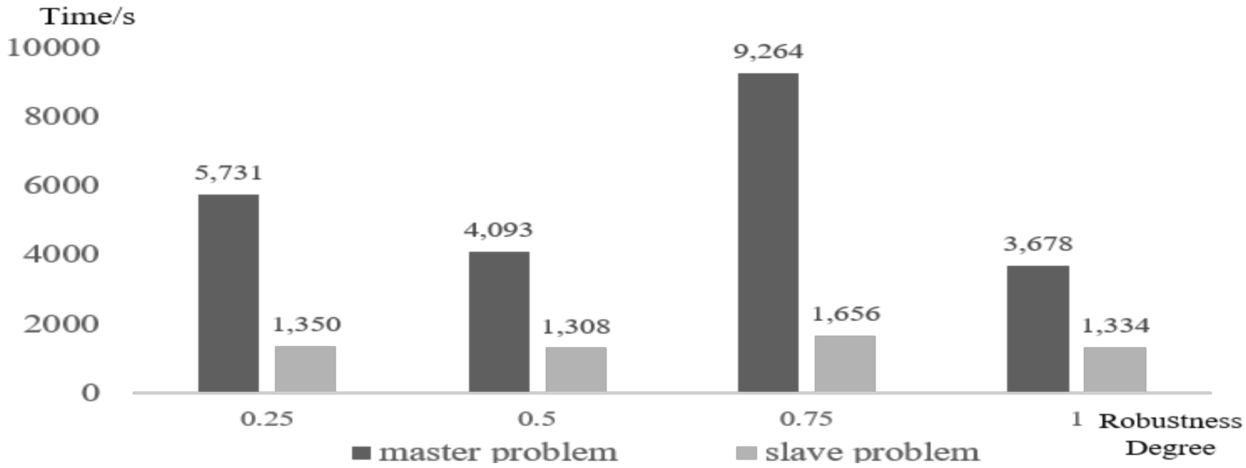
Look Back (July 2018-June 2019)

- **Integrating Demand Side Resources into Multi-Stage Robust Generation and Transmission Expansion Planning**
  - Case Studies via the IEEE RTS-96 test system
    - Impact of different participation levels of demand side resources
    - Impact of different investment costs (IC) of demand side resources
    - 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	$G_{3,1}G_{4,4}\mathbf{G_{7,3}G_{8,10}}$	$\mathbf{T_{1,2}}T_{2,1}T_{3,1}T_{4,1}$ $\mathbf{T_{5,8}}T_{7,1}T_{8,1}$	$\mathbf{D_{1,1}D_{2,8}}D_{3,1}D_{4,1}D_{5,1}$ $D_{6,1}D_{7,1}D_{8,1}D_{9,1}D_{10,1}$

Look Back (July 2018-June 2019)

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



Look Back (July 2018-June 2019)

- **Dissemination of research results**
  - Journal Publication
    - C. Dai, L. Wu, B. Zeng, and C. Liu, “A System State Model Based Multi-Period Robust Generation, Transmission, and Demand Side Resource Co-Optimization Planning,” IET Generation, Transmission & Distribution, DOI:10.1049/iet-4gtd.2018.5936, November 2018.
    - X. Cao, J. Wang, and B. Zeng, “Networked Microgrids Planning Through Chance Constrained Stochastic Conic Programming,” to appear in IEEE Transactions on Smart Grid.
  - Some mathematical models and computational algorithms developed in this project have been integrated into graduate courses of collaborating universities
    - *EE590 “Smart Grid”* in Spring 2019 at Stevens Institute of Technology. In Spring 2019, 14 undergraduate students and 2 graduate students enrolled in this class.

Looking Forward (July 2019- June 2020)

- **Planned activities and schedule for July 2019- June 2020**
  - Further evaluate effectiveness of the developed approaches via additional large-scale system tests including the WECC 243-bus system, and to revisit and revise the models and algorithms for further improvements.
    - The WECC 243-bus system is a real-world test case originally designed for UC problems, which includes 451 existing transmission lines.
    - 58 potential locations are considered to install new coal-fired generators, combustion generators, as well as wind and solar farms. New lines can be built following existing corridors to enhance transmission capabilities.
    - We will also simulate cases with an annual capacity phasing-out rate for conventional generations, and evaluate whether it is feasible to reach a 100% renewable penetration environment in a multi-year planning process.
  - Disseminate research results, 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.
  - Prepare project final report.

Thank you!

DE-OE0000842
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