# A Unified Framework for Defining and Measuring Flexibility in Power System

*Optimization and Equilibrium in Energy Economics Workshop*

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# Outline

- ***WHY*** do we need a framework for flexibility?
- ***WHAT*** is flexibility?
- ***HOW*** to measure flexibility?
- Applications

# Motivation

- New England power system faces an increasing level of uncertainty as more renewable resources are integrated
  - 700 MW wind plants
  - 1200 MW solar (including behind-meter solar panels)
- This requires the system to have the ability to react to the rapid change of the system condition within an acceptable time frame and cost threshold
- The notion of flexibility recently has been drawing significant attention

# Flexibility Literature Review

- Use additional reserve to provide flexibility
  - Leite da Silva, et. al. (2010), NREL (2010),
- Ramping products
  - MISO, CAISO
- Definition
  - Lannoye, et al. (2013): the ability of a system to deploy its resources to respond to changes in the demand not served by variable generation
  - Capasso, et al. (2005), Bresesti, et al. (2003): the attribute of the transmission system to keep up a desired standard of reliability at reasonable operation costs, when generation scenarios changes.
- Indices
  - Insufficient ramping resource expectation (IRRE), Lannoye, et al. (2013)
  - A flexibility index based on generator's ramping capability and generating capacity, Ma, et al. (2013)
  - Balancing reserve, Menemenlis et al. (2011)

# Need for a Unified Framework for Flexibility

- There are many flexibility measures provided for different aspects of flexibility using various approaches
- There is a lack of a general framework that encompasses different concepts and techniques
- A unified flexibility framework
  - Allow flexibility to be explicitly considered in the system design
  - Allow quantitatively compare across different options to increase the system flexibility

# What is Flexibility

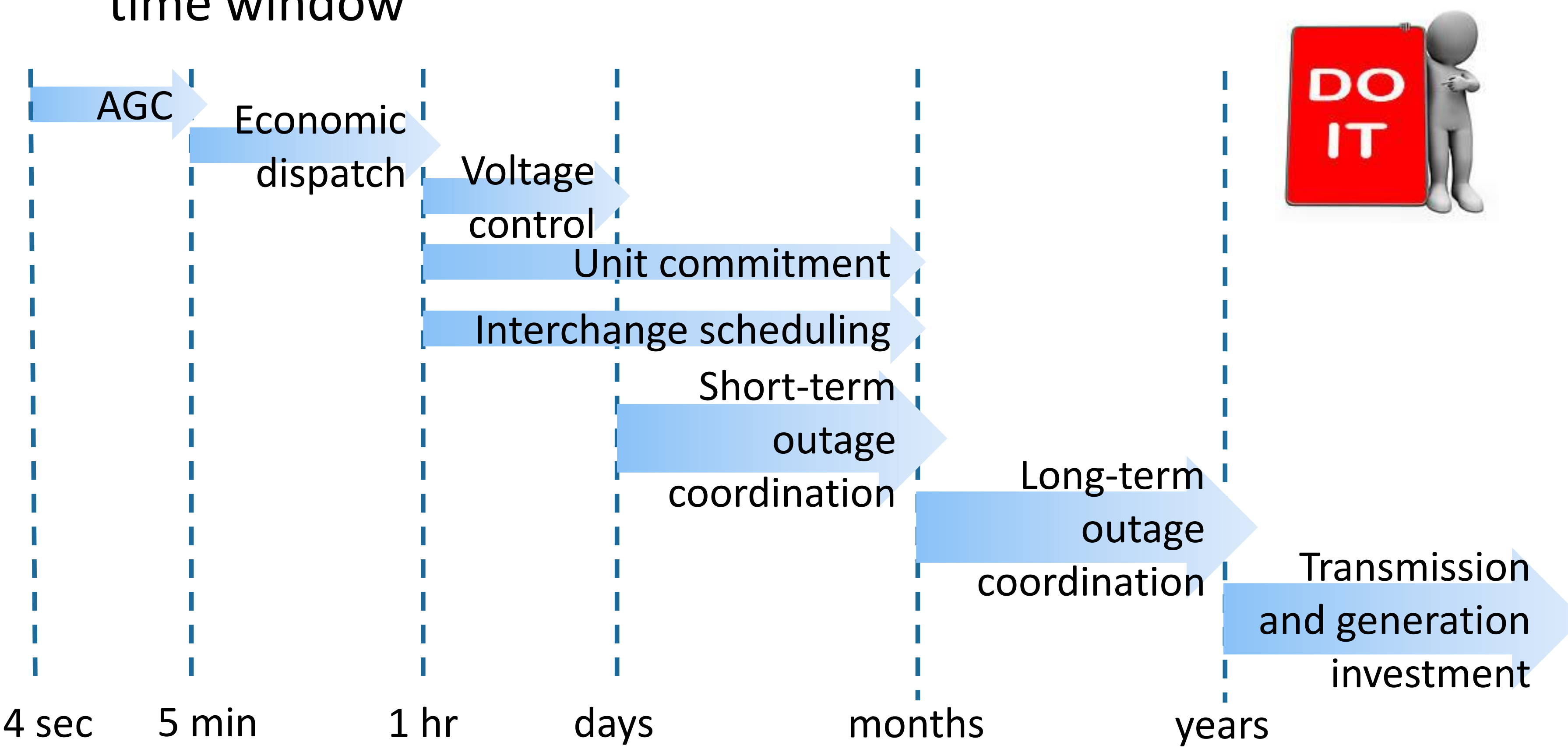
- Flexibility is the ability of a system to respond to a range of uncertain future states by taking an alternative course of action within acceptable cost threshold and time window.
- Four key elements
  - Time
  - Action
  - Uncertainty
  - Cost
- Serve as a basis for constructing measures of flexibility

# Time

- Indicate how fast the system reacts to a disturbance and restore the system to its normal state.
- Seconds, minutes, hours, days, months, and years
- A system might have sufficient capacity to cope with demand growth in a year, but not enough capability to adapt to hourly load fluctuations.

# Action

- The corrective actions that can be taken within the response time window



# Uncertainty

- The lack of complete information of the future system state
- Component failure, load forecast errors, renewable generation variability
- The magnitude of uncertainty determines how much flexibility a system requires to handle uncertainty
  - A system that is flexible with respect to loss of one element (N-1 contingencies) may not be flexible for loss of two elements (N-2 contingencies)

# Cost

- The response cost depends on the corrective action.
- Cost threshold
  - Some corrective actions become uneconomical, and will not be considered.
- Minimize response cost
  - The most economic corrective actions are sought in response to uncertainty

# Illustrative Example of the Four-Element Framework

- Ma, Kirshen, Silva and Belhomme, "Optimizing the flexibility of a portfolio of generating plants to deal with wind generation," in IEEE and Energy Society General Meeting, San Diego, CA, 2011
- Response time: one year
- Action: generation expansion, unit commitment and economic dispatch
- Uncertainty: load level, load profile, and renewable generation
- Cost: minimize the sum of dispatch, commitment and investment cost

# How to Measure Flexibility

- Given a response time window, a response cost threshold, and a target variation range, a flexibility index is defined as follows:

$$F = \frac{\text{The \textbf{largest variation range} of uncertainty the system can accommodate}}{\text{The \textbf{target variation range} of uncertainty the system aim to accommodate}}$$

- The magnitude of the *target range* reflects decision makers' risk preference
- Does system has enough flexibility to cover the targeted uncertainty?
- Quantify the system's safety margin

# Variation Range Maximization

$$\max_{u^{LB},u^{UB},a(.)} \| u^{UB} - u^{LB} \|$$

Maximize the size of the variation range of uncertainty

s.t. $$Aa(u) + Bu \le b \quad \forall u \in [u^{LB}, u^{UB}]$$

The system's reaction to uncertainty via corrective actions

$$c^T a(u) \le \bar{C} \quad \forall u \in [u^{LB}, u^{UB}]$$

The budget for corrective actions

$$[u^{LB}, u^{UB}] \subseteq [u^{LB,target}, u^{UB,target}]$$

| | |
|---|---|
| $u^{LB}, u^{UB}$ | The lower and upper bounds of the variation range |
| $u^{LB,target}, u^{UB,target}$ | The lower and upper bounds of the target variation range |
| $a(u)$ | The corrective actions responding to uncertainty |
| $\bar{C}$ | The response cost threshold |

# Not a Standard Robust Optimization Problem

- A standard robust optimization problem:

$$\min_{a(.)} \left( \max_{u \in [u^{LB,*}, u^{UB,*}]} d^T a(u) \right)$$

$$\text{s.t.} \quad Aa(u) + Bu \leq b, \forall u \in [u^{LB,*}, u^{UB,*}]$$

  – Given an uncertainty set, how to design the system to accommodate the worst case?
  – The uncertainty set is pre-determined

- The variation range maximization problem:

$$\max_{u^{LB}, u^{UB}, a(.)} \| u^{UB} - u^{LB} \|$$

$$\text{s.t.} \quad Aa(u) + Bu \leq b, \forall u \in [u^{LB}, u^{UB}]$$

$$c^T a(u) \leq \bar{C}, \forall u \in [u^{LB}, u^{UB}]$$

  – Given the system’s capability, what is the largest uncertainty set it can accommodate?
  – The uncertainty set is to be determined

# Solution Methodology 1: Affine Policy

- Assume the corrective action linearly responses to uncertainty

$$a(u) = l + Lu$$

- Reformulate the variation range maximization problem

$$\max_{u^{LB}, u^{UB}} e^T \left(u^{UB} - u^{LB}\right)$$

$$\text{s.t.} \quad A(l + Lu) + Bu \le b, \forall u \in [u^{LB}, u^{UB}]$$

$$c^T (l + Lu) \le \bar{C}, \forall u \in [u^{LB}, u^{UB}]$$

- Using the strong duality theory, the problem becomes
  - Linear program if the coefficients of the affine policy are pre-specified
  - Bilinear program otherwise

# Solution Methodology 2: Benders Decomposition

- Variable substitution for $u \in [u^{LB}, u^{UB}]$

$$u = z \cdot u^{LB} + (1-z) \cdot u^{UB}, \forall z \in [0,1]$$

- Two-stage robust optimization

$$\max_{u^{LB}, u^{UB}, a(.)} \| u^{UB} - u^{LB} \|$$

s.t.

$$Aa(z) + B(z \cdot u^{LB} + (1-z) \cdot u^{UB}) \le b, \quad \forall z \in [0,1]$$

$$c^T a(z) \le \bar{C}, \quad \forall z \in [0,1]$$

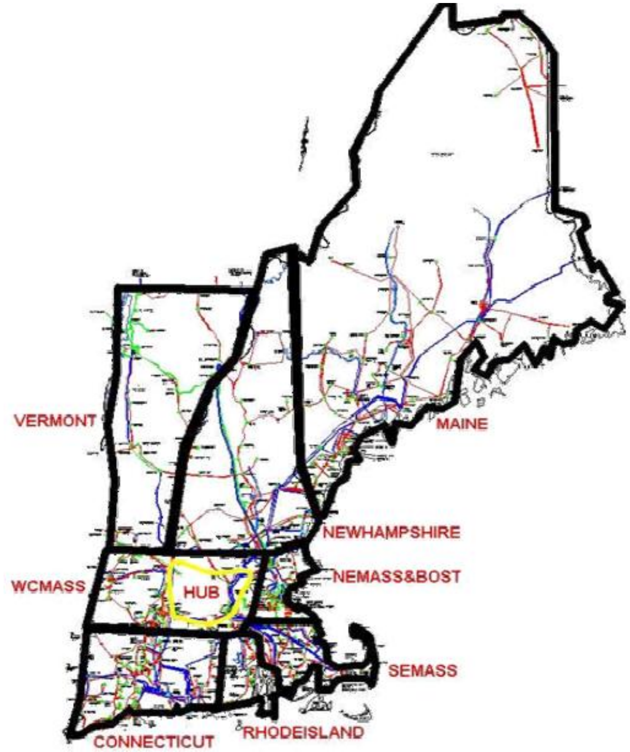
$$[u^{LB}, u^{UB}] \subseteq [u^{LB,target}, u^{UB,target}]$$

- Benders decomposition can be used to solve the robust optimization problem

# Real-Time System Flexibility

- Response time window: 15 min
- Corrective action: dispatch of conventional units
- Cost: response cost threshold
- Uncertainty: wind output uncertainty

- ISO New England system
  - 2816 buses
  - 150 online conventional generators
  - 6 wind generators
    (artificially scaled up to 2479 MW in total)



# Formulation

$$\max_{d^{UB},d^{LB},p(.)} \sum_{n=\text{RAND}} (d_{n,T}^{UB} - d_{n,T}^{LB})$$ Maximize the total net load variation range

s.t.

$$\sum_{j=\text{conv}} p_{j,T}(\mathbf{d}) + \sum_{n=\text{rand}} d_{n,T} = 0, \quad \forall \mathbf{d} \in [\mathbf{d}^{LB}, \mathbf{d}^{UB}]$$ Energy balance

$$\sum_{n} SF_{n,l} \times (p_{j(n),T}(\mathbf{d}) + d_{n,T}) \le F_l^{\max}, \quad \forall l = TL, \quad \forall \mathbf{d} \in [\mathbf{d}^{LB}, \mathbf{d}^{UB}]$$ Transmission constraint

$$p_{j,0} - \Delta_j^{dn} \times T \le p_{j,T}(\mathbf{d}) \le p_{j,0} + \Delta_j^{up} \times T, \quad \forall j = conv \quad \forall \mathbf{d} \in [\mathbf{d}^{LB}, \mathbf{d}^{UB}]$$ Ramping capability

$$p_{j,T}^{\min} \le p_{j,T}(\mathbf{d}) \le p_{j,T}^{\max}, \quad \forall j = conv, \quad \forall \mathbf{d} \in [\mathbf{d}^{LB}, \mathbf{d}^{UB}]$$ Capacity constraint

$$\sum_{j=\text{CCU}} c_j \times p_{j,T}(\mathbf{d}) \le \bar{C}_T, \quad \forall \mathbf{d} \in [\mathbf{d}^{LB}, \mathbf{d}^{UB}]$$ Dispatch cost budget

$\mathbf{d}$ Net load uncertainty = load – wind output

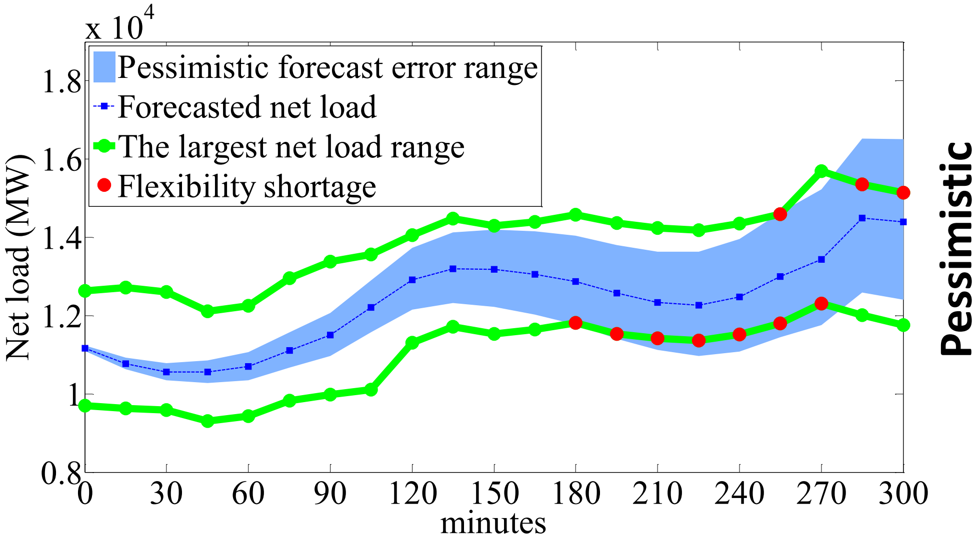
$p_{j,T}$ Output of generator *j*

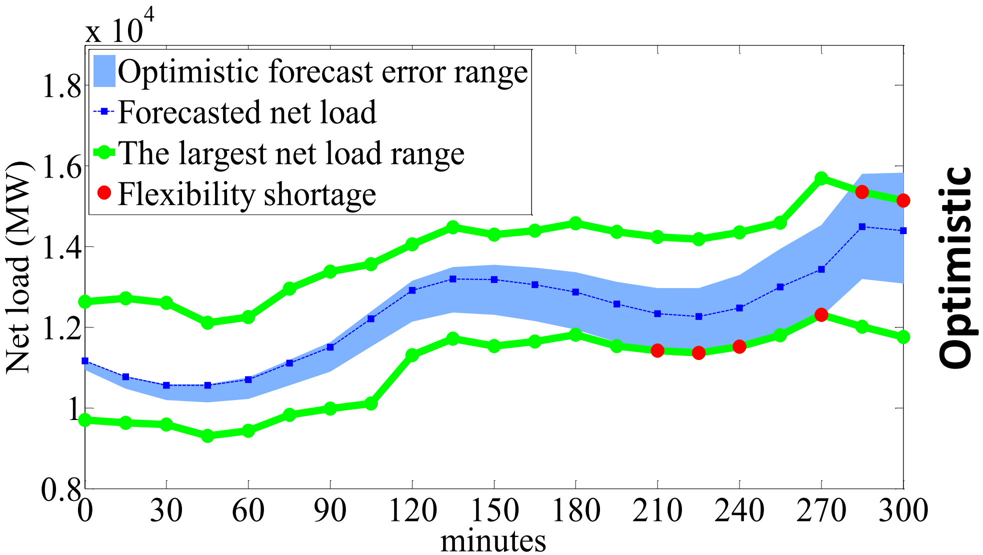
$SF_{n,l}$ Shift factor

$c_j$ Dispatch cost

$\Delta_j$ Ramp rate

# Impact of Uncertainty

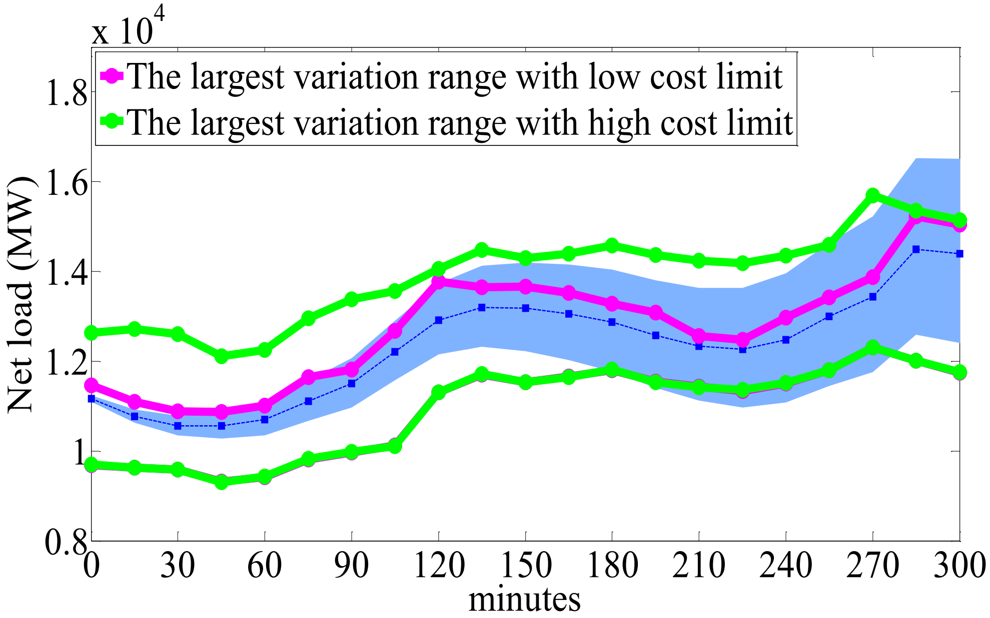



- The risk tolerance level can be quantified by the target variation range
  - Pessimistic target range
  - Optimistic target range

- The degree of flexibility depends on decision makers' risk tolerance level

# Impact of Cost




- Two levels of cost threshold
  - High: $10 Million
  - Low: 1.01×dispatch cost of meeting the forecasted net load
- The smaller the cost threshold, the narrower the largest variation range.
- Downward ramping capability is less affected by the cost limit than the upward ramping capability.

# Application 1: Zonal Ramping Requirements

- A situation Awareness tool
  - By visualizing the flexibility metrics, operators can easily spot the flexibility shortage events in advance
- Real-time look-ahead application
  - Imposing zonal ramping requirements to prevent flexibility shortages
- Upward ramping requirement

  at a zone z

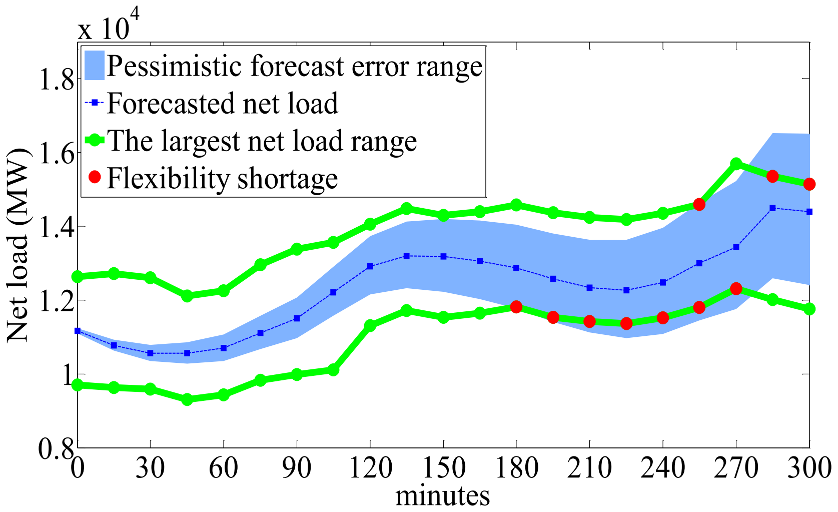
$$\sum_{n \in N_z} \max\left(d_n^{UB,target} - d_n^{UB}, 0\right)$$

- Downward ramping requirement

  at a zone z

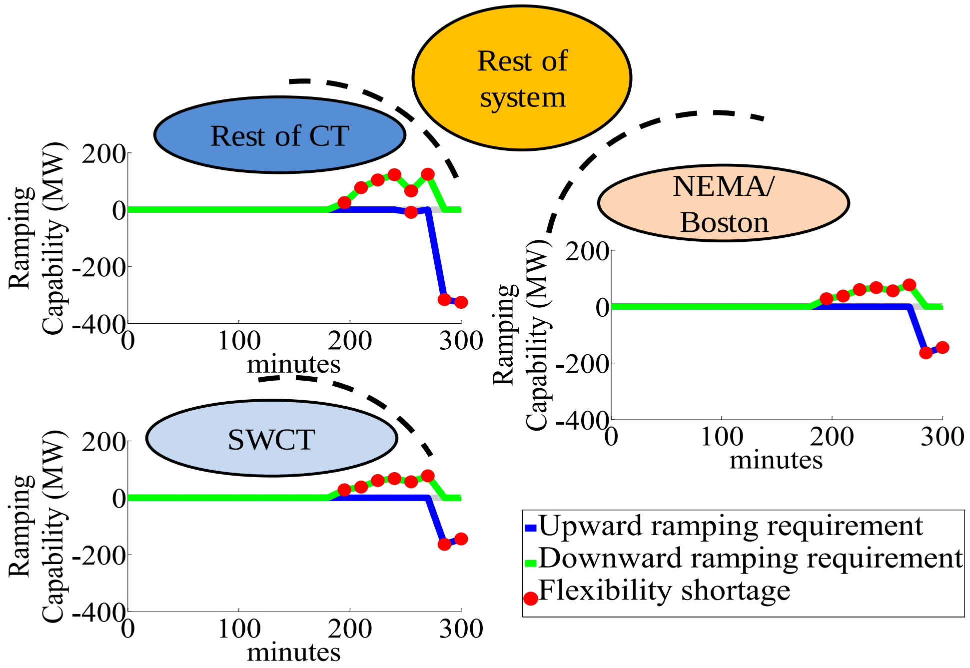
$$\sum_{n \in N_z} \max\left(d_n^{LB} - d_n^{LB,target}, 0\right)$$

- This is a research project.



# Example: ISO New England System

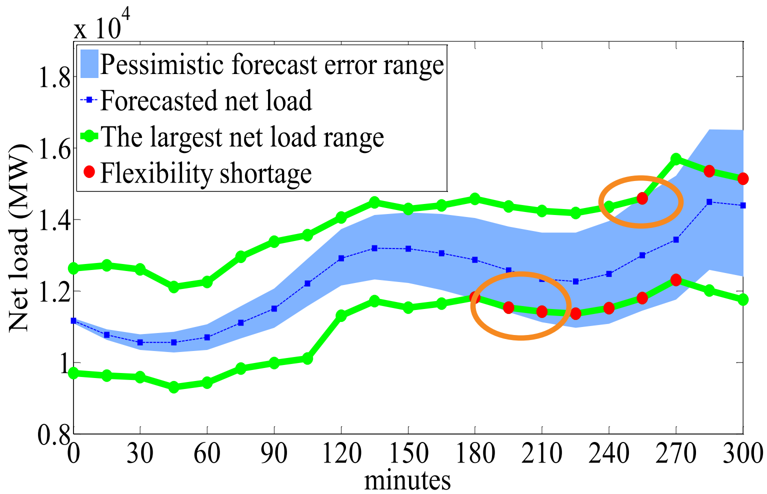
- Zonal ramping requirements



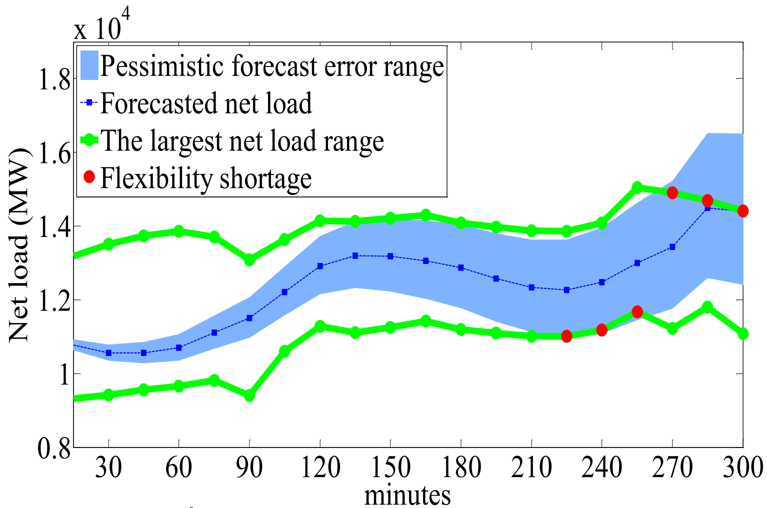

- ❑Northeast Massachusetts (NEMA)/Boston
- ❑Southwest Connecticut (SWCT)
- ❑The rest of Connecticut

- The system can prepare sufficient ramping capability at where it is needed to avoid possible flexibility shortage in the future.

# Effect of Zonal Ramping Requirements




Without ramping requirement



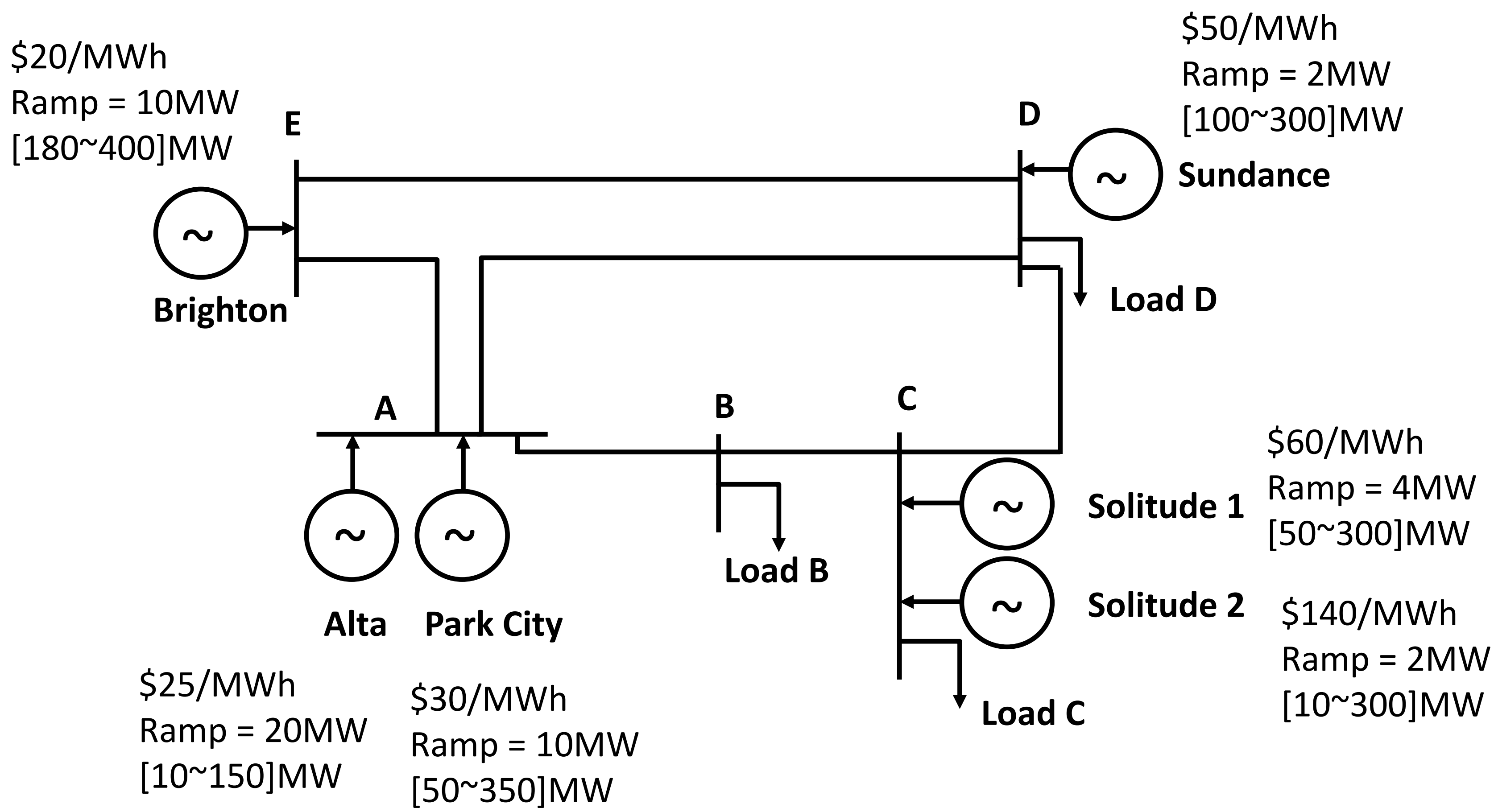

With ramping requirement

- System is repositioned under the zonal ramping requirements
- Several downward/upward flexibility shortage events are eliminated
- Effectively deter early flexibility deficit
- Provide additional time for operators to solve flexibility issues

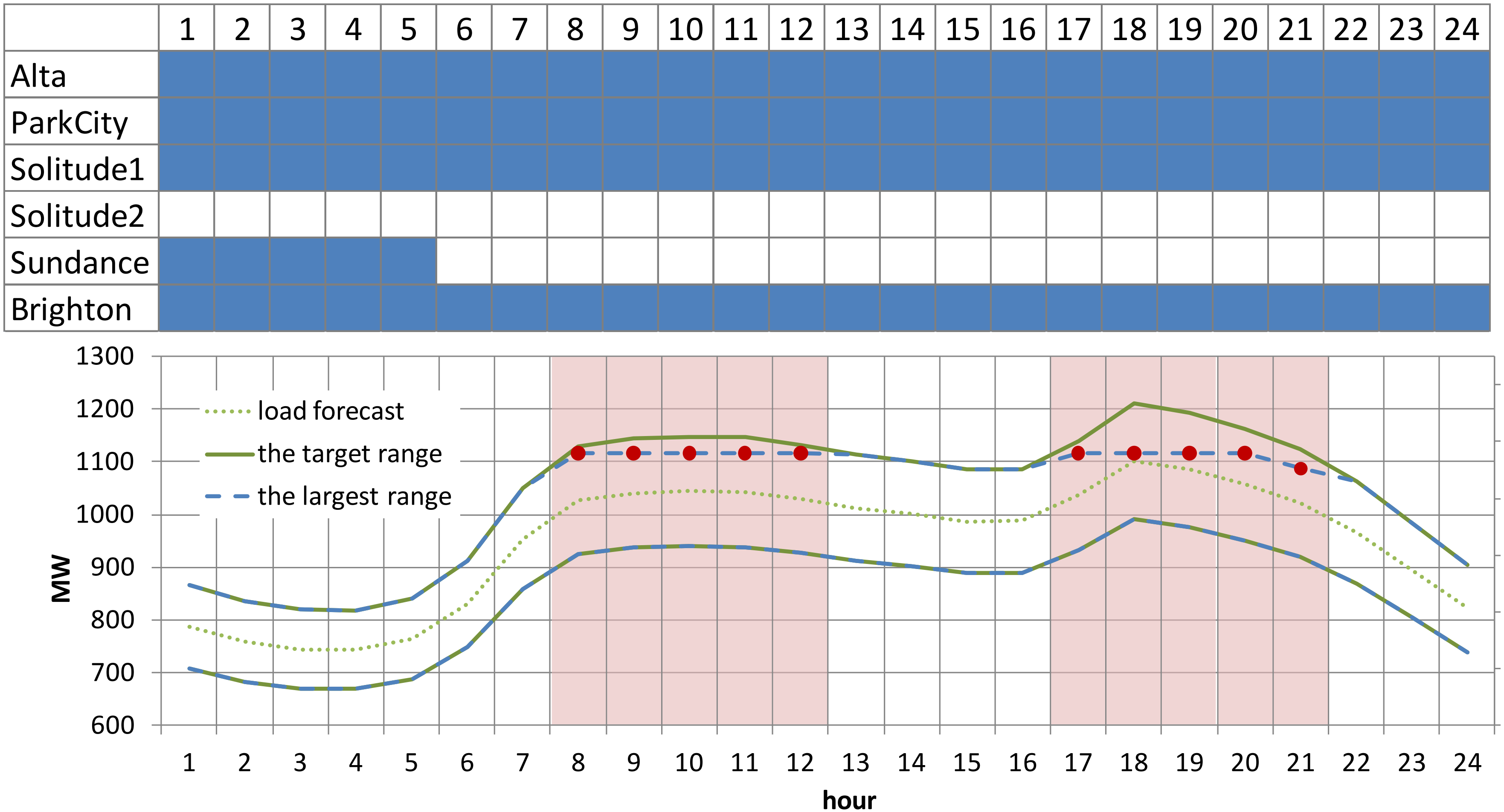
# Application 2: Additional Unit Commitment

- Deterministic unit commitment is to meet the forecasted load
- The deterministic commitment schedule may be highly suboptimal or infeasible when the actual system conditions significantly differ from the forecast.
- Which is the next most flexible offline unit that can be turned on to provide additional flexibility to respond to uncertainties?
- This is a research project. The potential application is the reserve adequacy assessment.

# Example: Five-Bus System



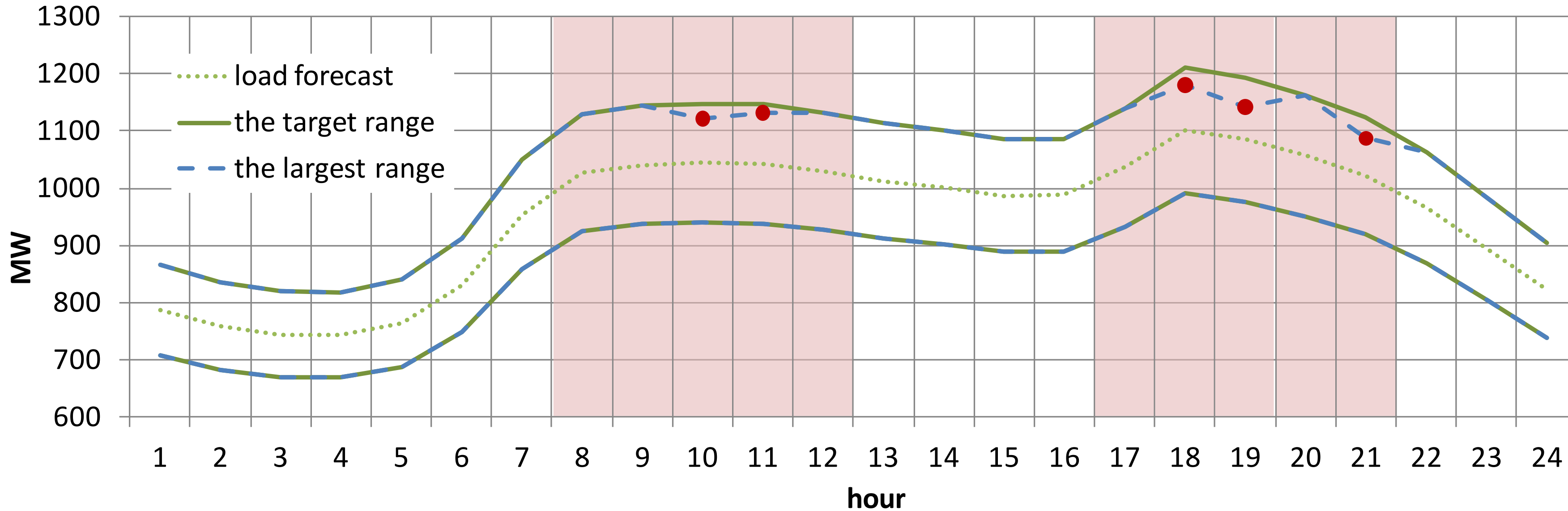
# Deterministic UC Result




The upper bound of the largest range becomes flat after hour 8 due to the lack of upward ramping capability

# Sundance Commitment Result

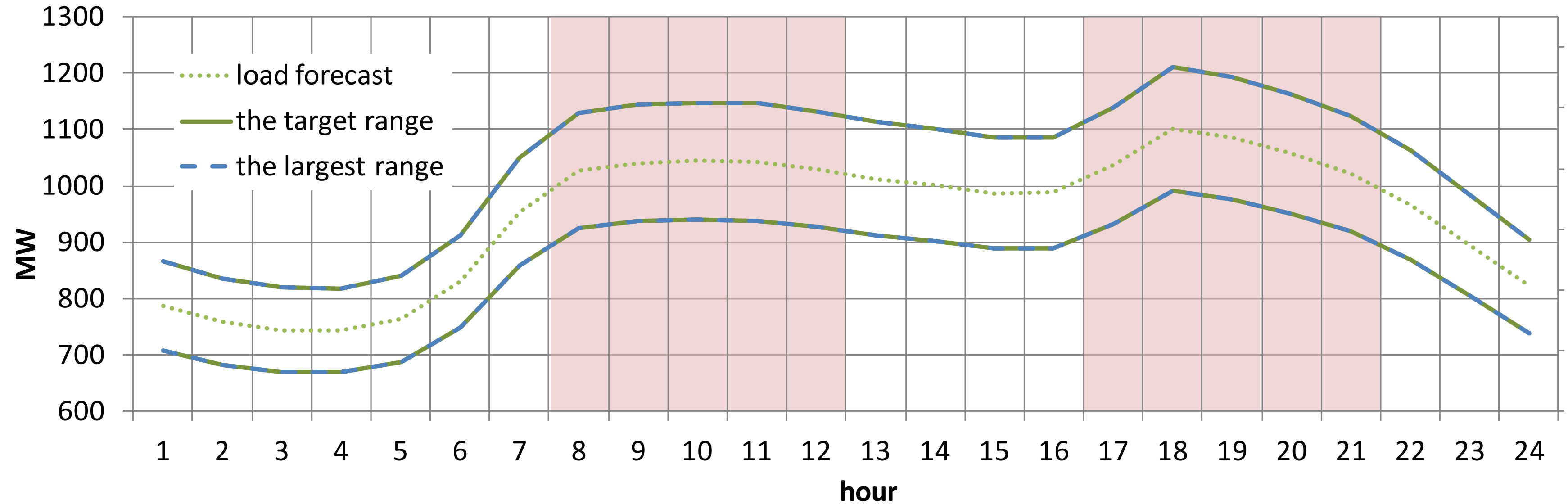
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alta | | | | | | | | | | | | | | | | | | | | | | | | |
| ParkCity | | | | | | | | | | | | | | | | | | | | | | | | |
| Solitude1 | | | | | | | | | | | | | | | | | | | | | | | | |
| Solitude2 | | | | | | | | | | | | | | | | | | | | | | | | |
| Sundance | | | | | | | | | | | | | | | | | | | | | | | | |
| Brighton | | | | | | | | | | | | | | | | | | | | | | | | |




Remove the flexibility shortage events at Hours 8, 9, 12,17, 20

# Solitude 2 Commitment Result

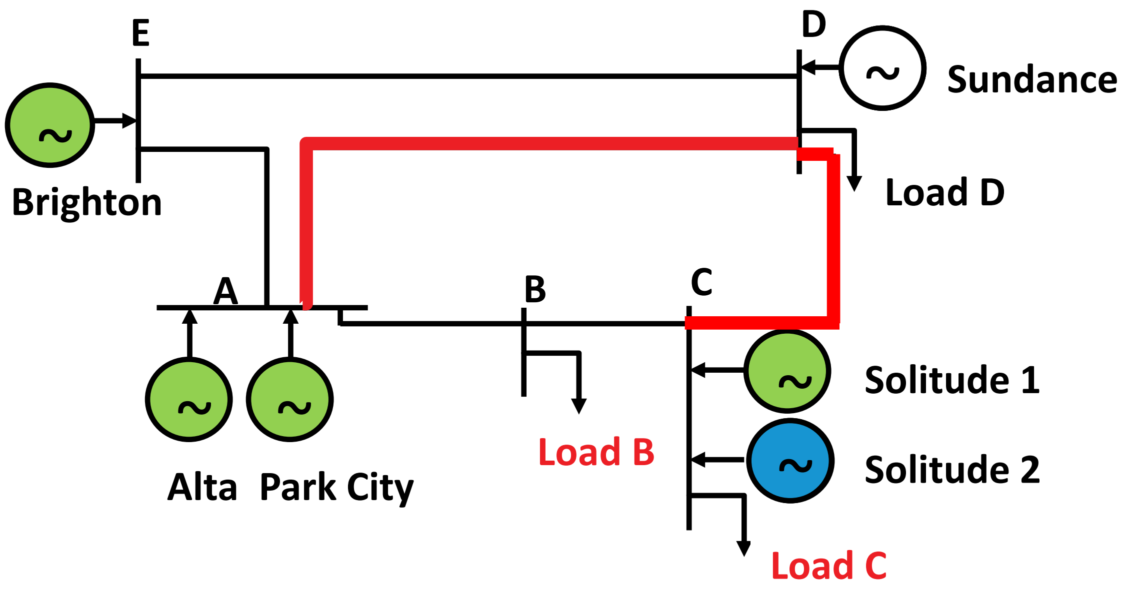
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alta | | | | | | | | | | | | | | | | | | | | | | | | |
| ParkCity | | | | | | | | | | | | | | | | | | | | | | | | |
| Solitude1 | | | | | | | | | | | | | | | | | | | | | | | | |
| Solitude2 | | | | | | | | | | | | | | | | | | | | | | | | |
| Sundance | | | | | | | | | | | | | | | | | | | | | | | | |
| Brighton | | | | | | | | | | | | | | | | | | | | | | | | |




Completely remove all the flexibility shortage events

# Further Analysis

- Solitude 2 is a more flexible than Sundance although their ramp rates are both 2MW/MIN
- The transmission congestion on lines AD and CD limits Sundance's ability of sending electricity to load B and C




ISO-NE PUBLIC

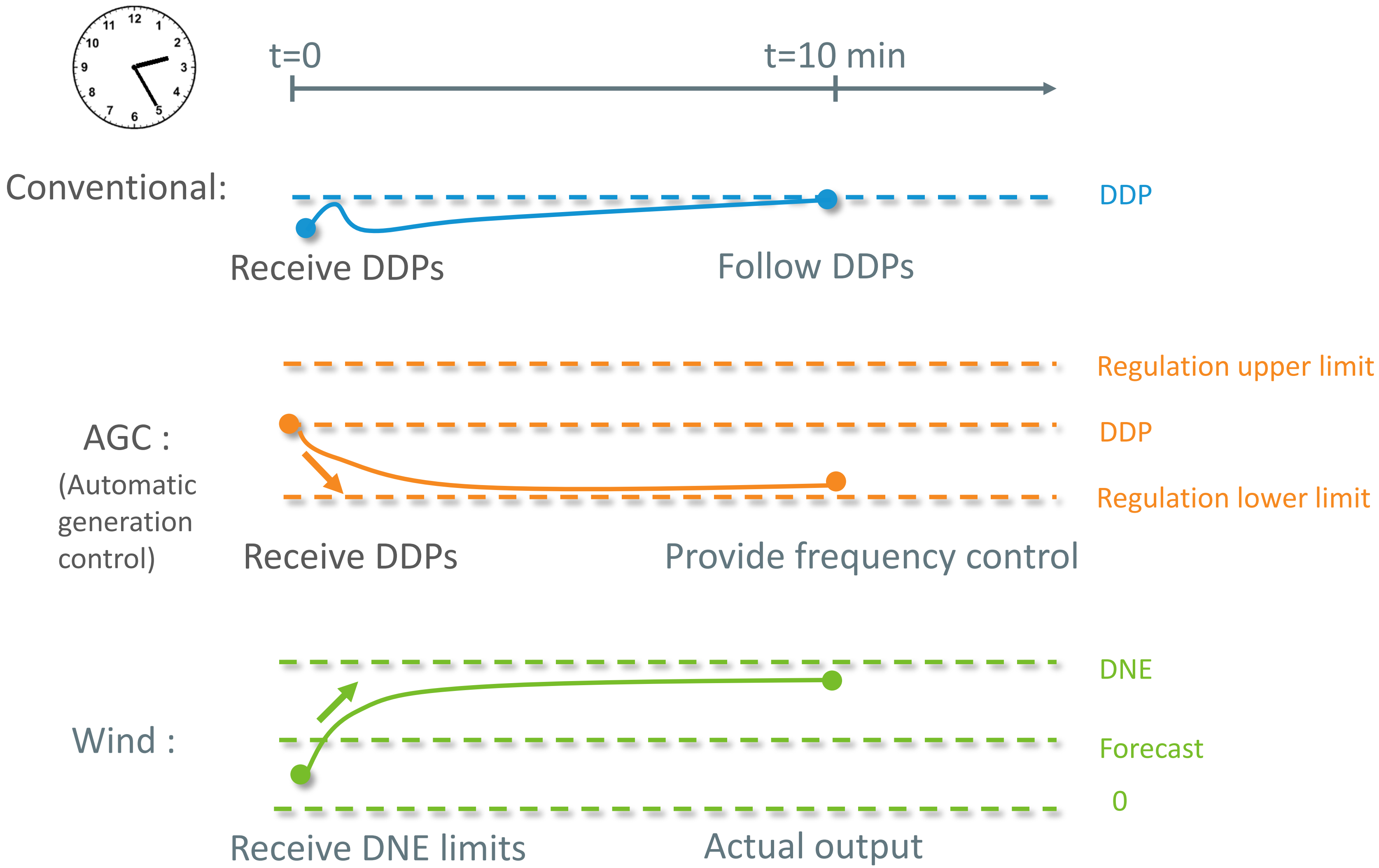
# Application 3: Do-Not-Exceed Limit Wind Dispatch

- Different from conventional generators, wind resources are
  - Low operating cost
    - Negative marginal cost
  - Variable
    - Increased level of uncertainty in the real-time operation
  - Non-dispatchable
    - Wind generation can be only curtailed when reliability issues arise
- How to design a dispatch framework that uses system's flexibility to better utilize the low cost wind resources while recognizing their variability?

# DNE Limit

- The dispatch instruction for a conventional generator is a ***desired dispatch point (DDP)***
- The dispatch instruction for a wind generator is *a* ***dispatch range (DNE Limit)***
- The DNE limit is the maximum amount of wind generation that the system can accommodate without causing any reliability issues.
- Benefits of DNE limit:
  - Provide a dispatch guideline for wind resources
  - Ensure reliable system operation
  - Allow low cost wind resources to provide as much energy as possible
- DNE limit will be in production in the 1st quarter of 2016.

# System Response under Wind Over-generation

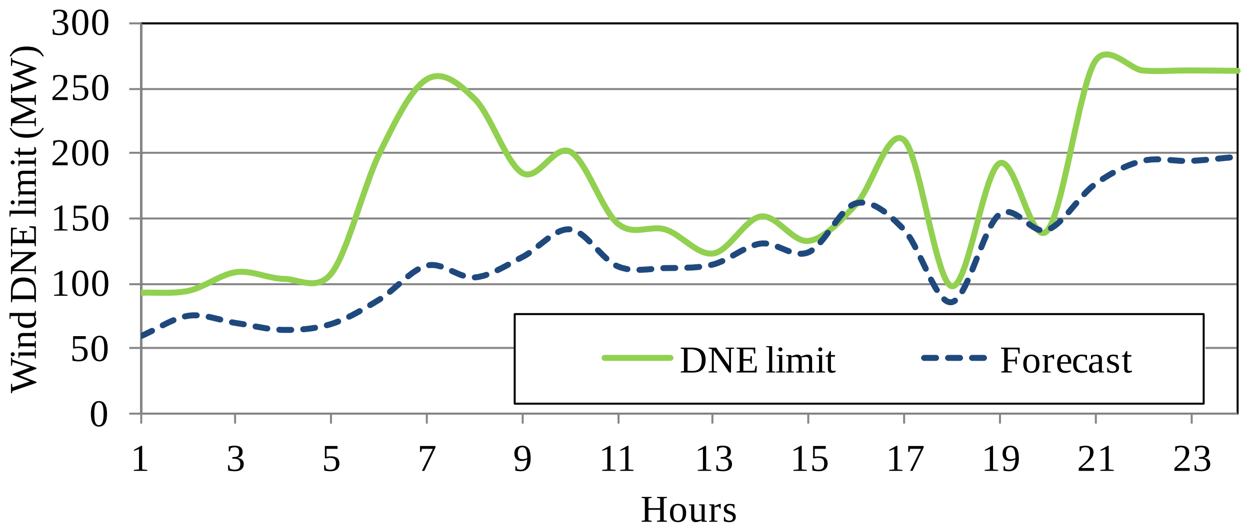


# DNE Limit Formulation

- Maximize the total DNE limit
- Subject To:
  - System is able to maintain energy balance under any wind output variations by AGC control
  - The flow on every transmission line remains within its limit under any realization of uncertain wind output by adopting AGC control
  - The AGC control must be subject to the corresponding physical limits
  - The output variation of a wind generator should be within its physical limits

# DNE Limit Example

- ISO New England system
  - 6 wind generators with total capacity of 250 MW
  - 1~3 AGC units with regulation capability of 20~140 MW



# Summary

- Propose a uniform framework for flexibility
- Propose a flexibility index under the uniform framework
- Compute the flexibility index using robust optimization techniques
- Zonal ramping requirement application
- Unit commitment application
- DNE limit application

# Questions