

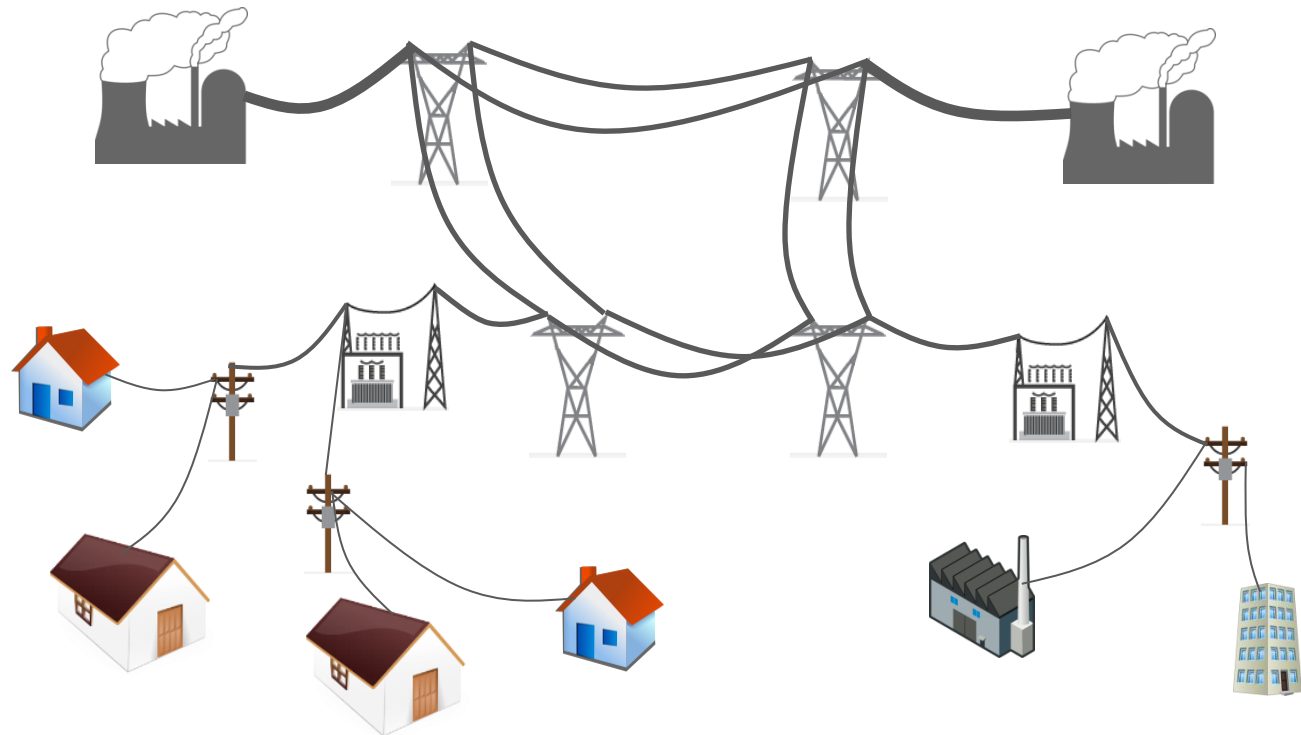
# Safety-Assured Collaborative Load Management in Smart Grids

Hoang Hai Nguyen <sup>1</sup>   Rui Tan <sup>1</sup>   David K. Y. Yau <sup>2,1</sup>

<sup>1</sup> Advanced Digital Sciences Center, Illinois at Singapore

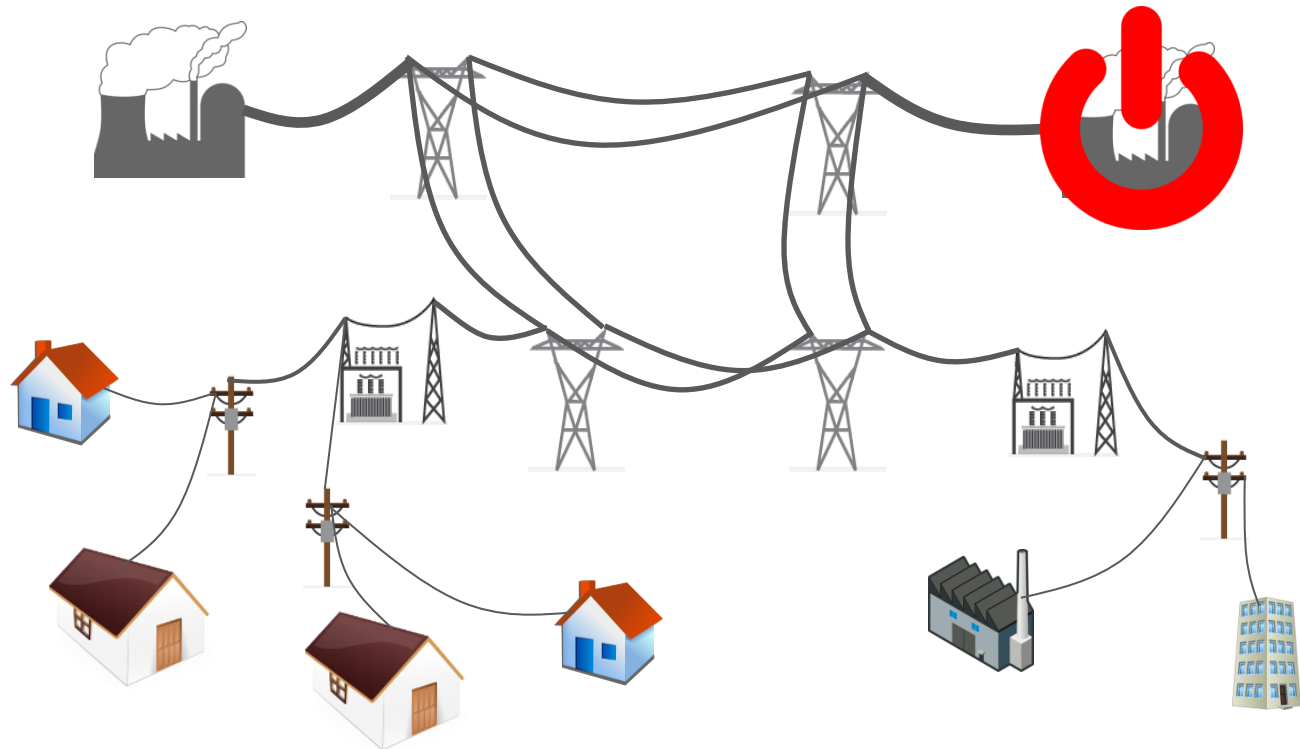
<sup>2</sup> Singapore University of Technology and Design

# Overloaded Grid is Unsafe



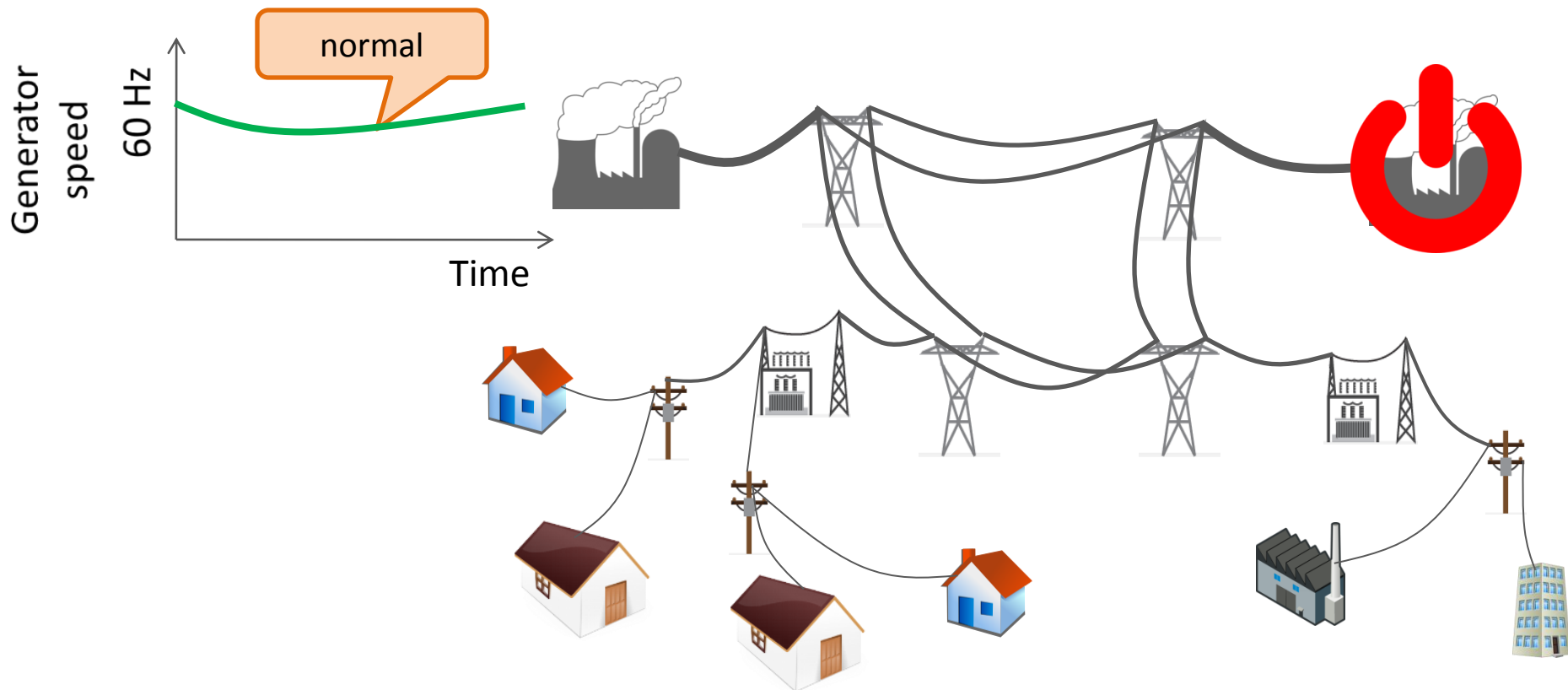
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- Loss of generation
  - Unexpected failures



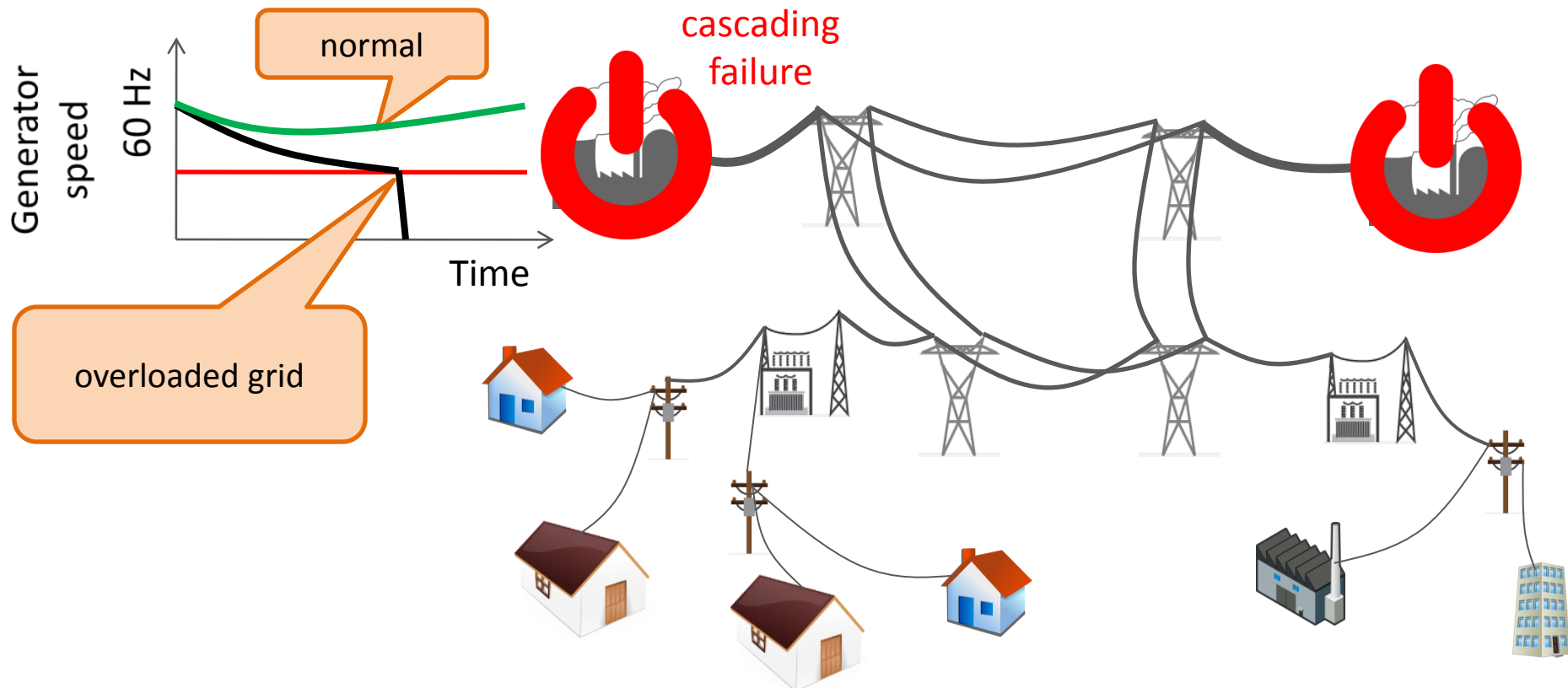
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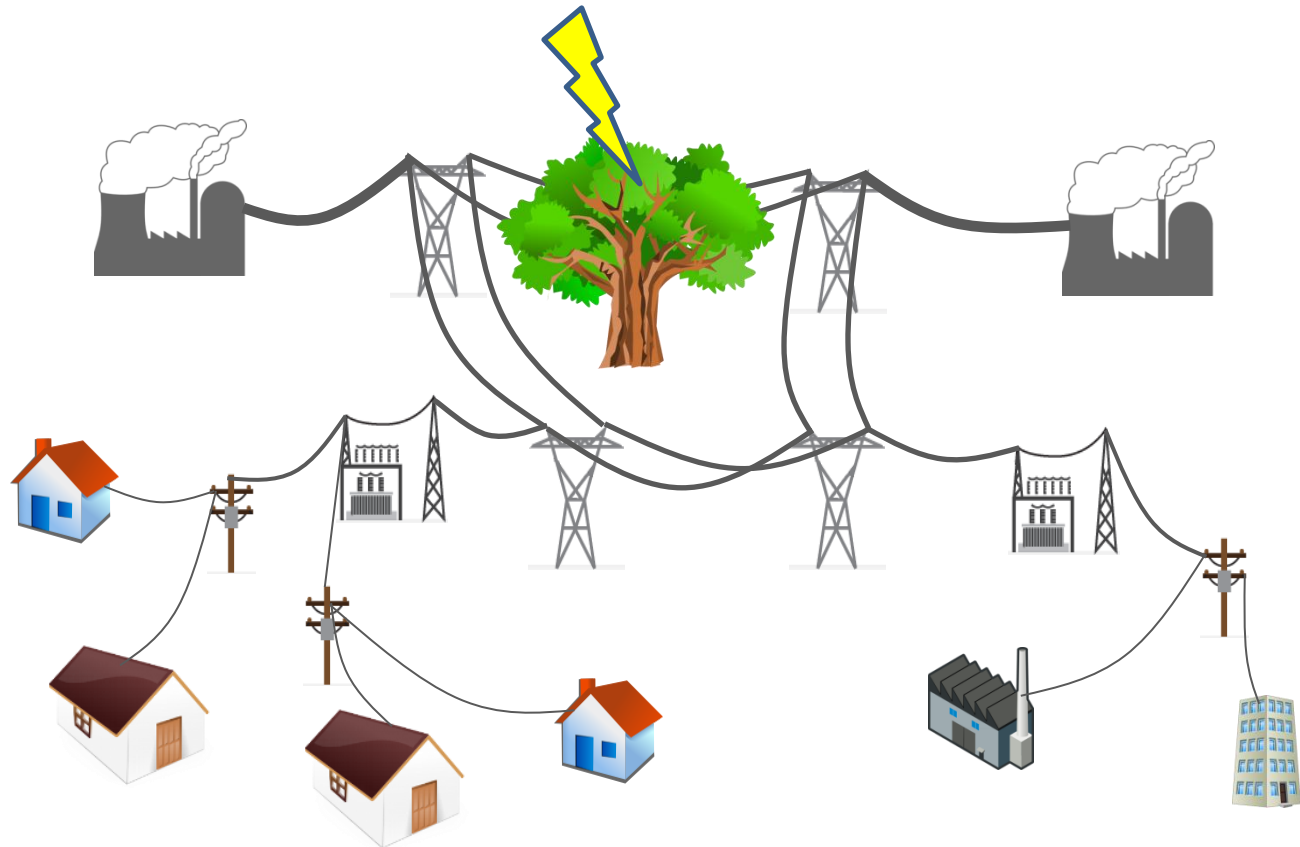
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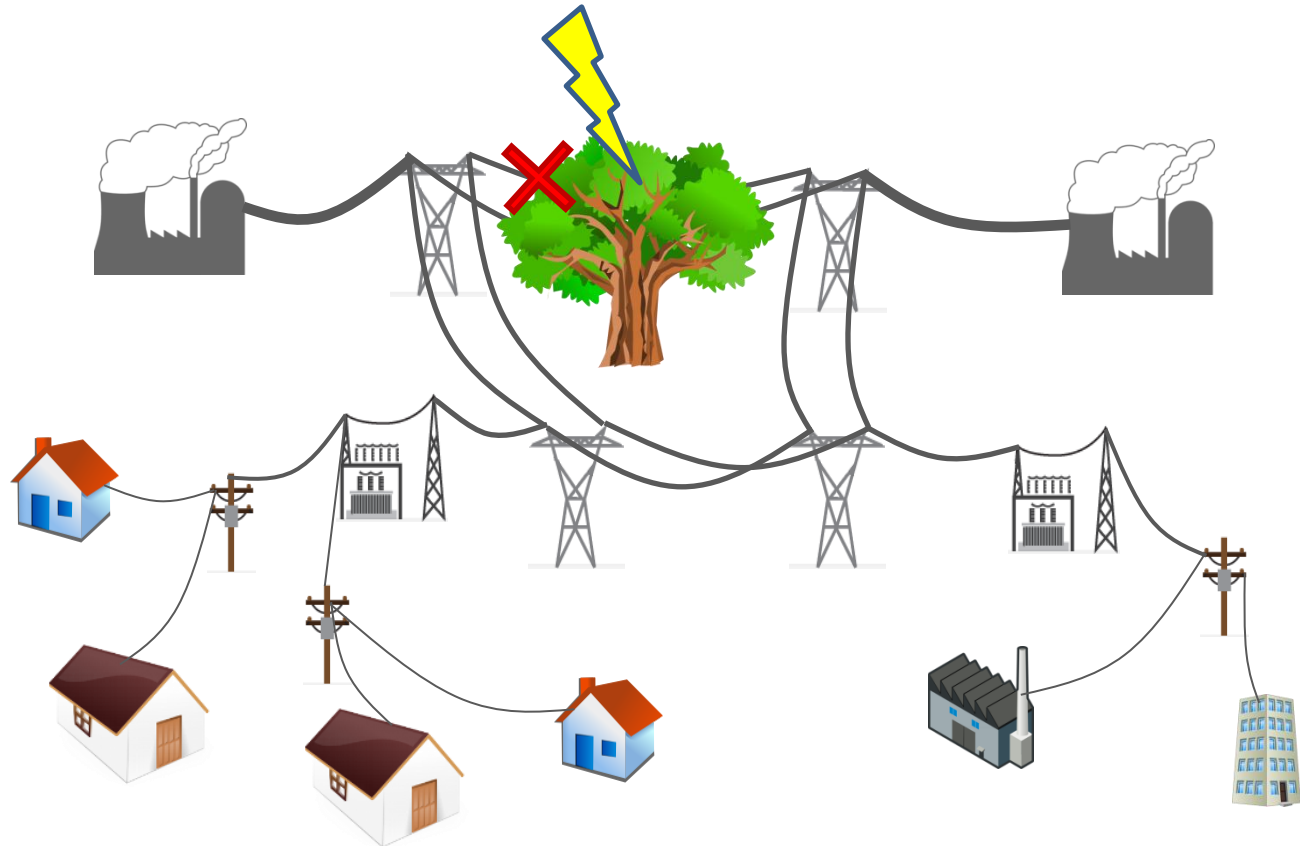
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- Loss of generation
  - Unexpected failures
- Transmission line short circuit
  - Hits by overgrown trees (2003 Northeast Blackout)



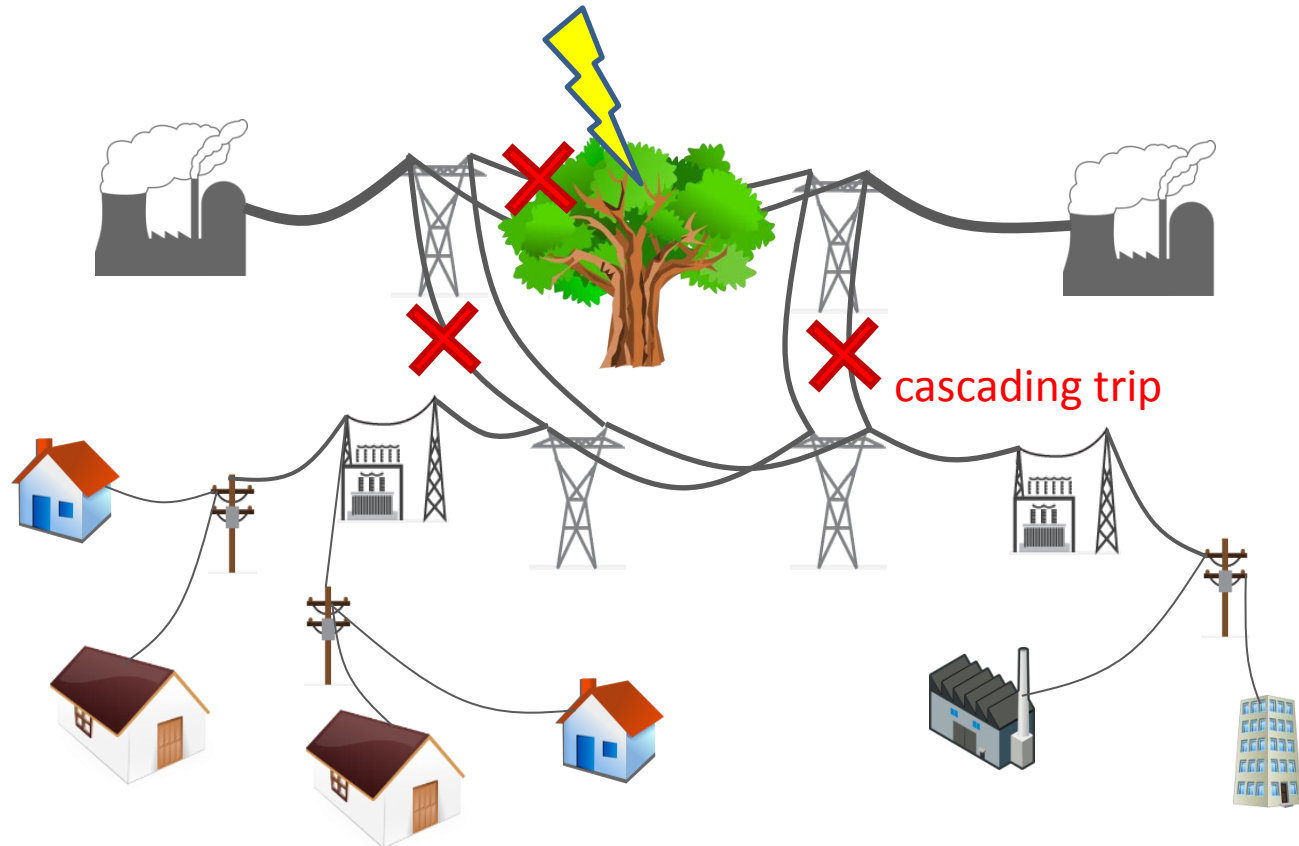
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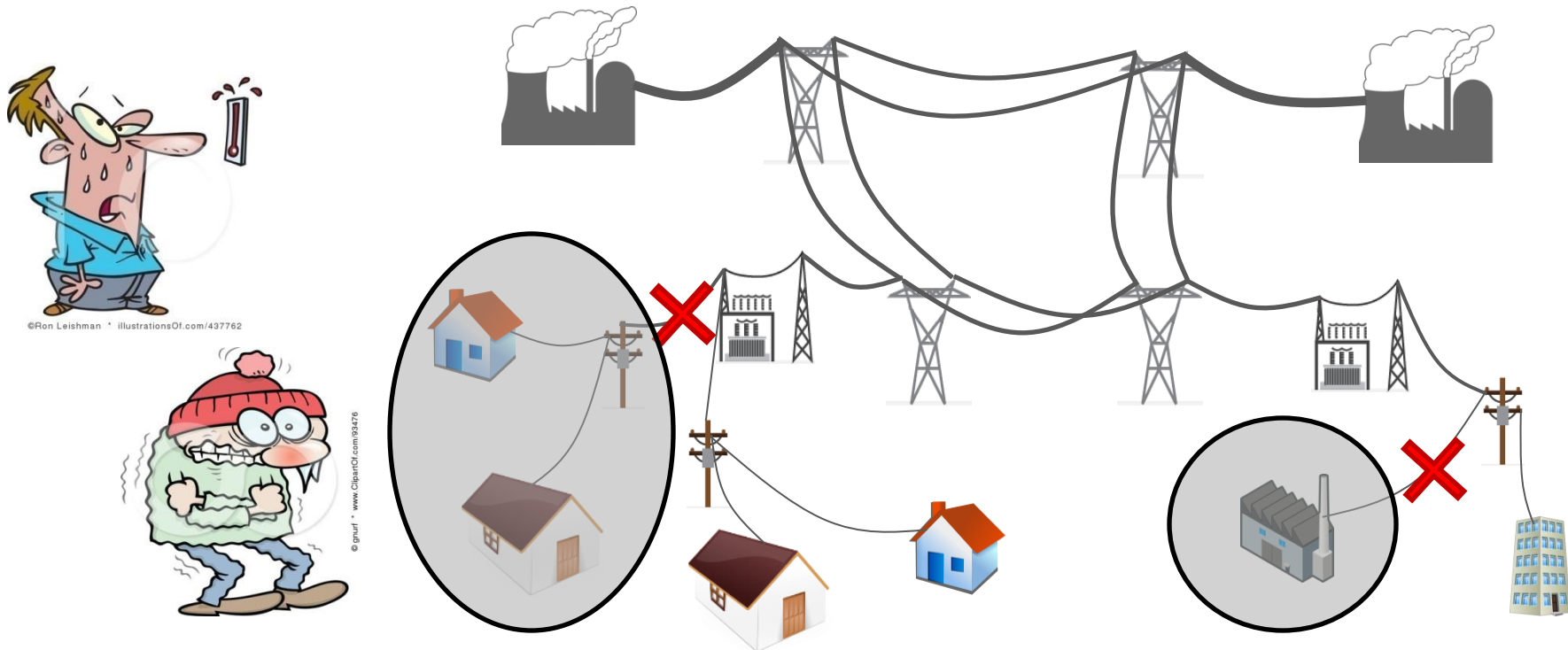
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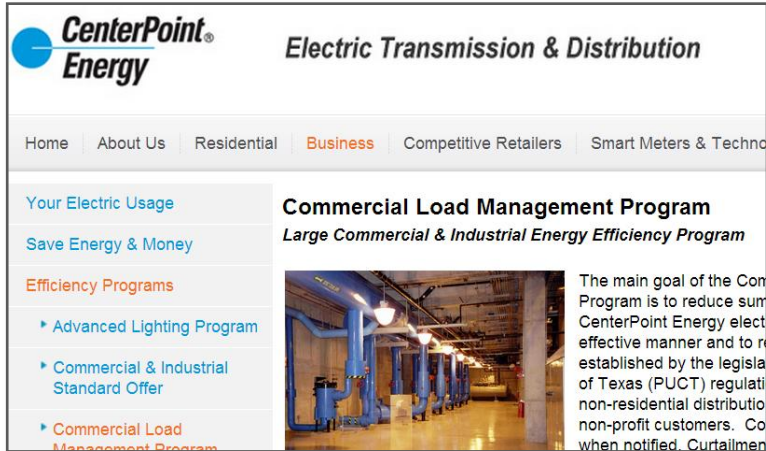


# Existing Solution: Load Shedding

- Disconnect some loads
  - When demand surges or failure detected
  - Resilient to (remaining) credible contingencies
- Unfair, uncomfortable



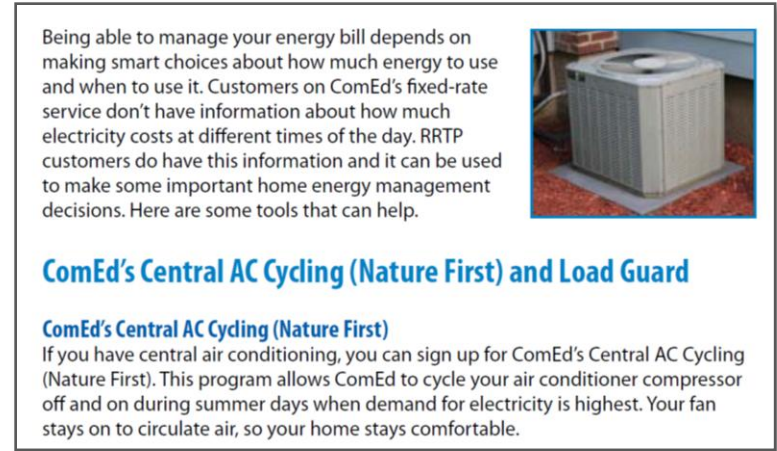
# New Opportunity: Load Curtailment



The screenshot shows the CenterPoint Energy website. The header includes the logo and the text "Electric Transmission & Distribution". The navigation menu has "Home", "About Us", "Residential", "Business", "Competitive Retailers", and "Smart Meters & Techno". The main content area is titled "Commercial Load Management Program" and "Large Commercial & Industrial Energy Efficiency Program". There is a sidebar with "Your Electric Usage", "Save Energy & Money", and "Efficiency Programs" which includes "Advanced Lighting Program", "Commercial & Industrial Standard Offer", and "Commercial Load Management Program". A central image shows an industrial facility with blue overhead cranes. Text to the right of the image describes the program's goal to reduce summer energy consumption.

Large commercial and industrial curtailment programs [CenterPoint Energy]

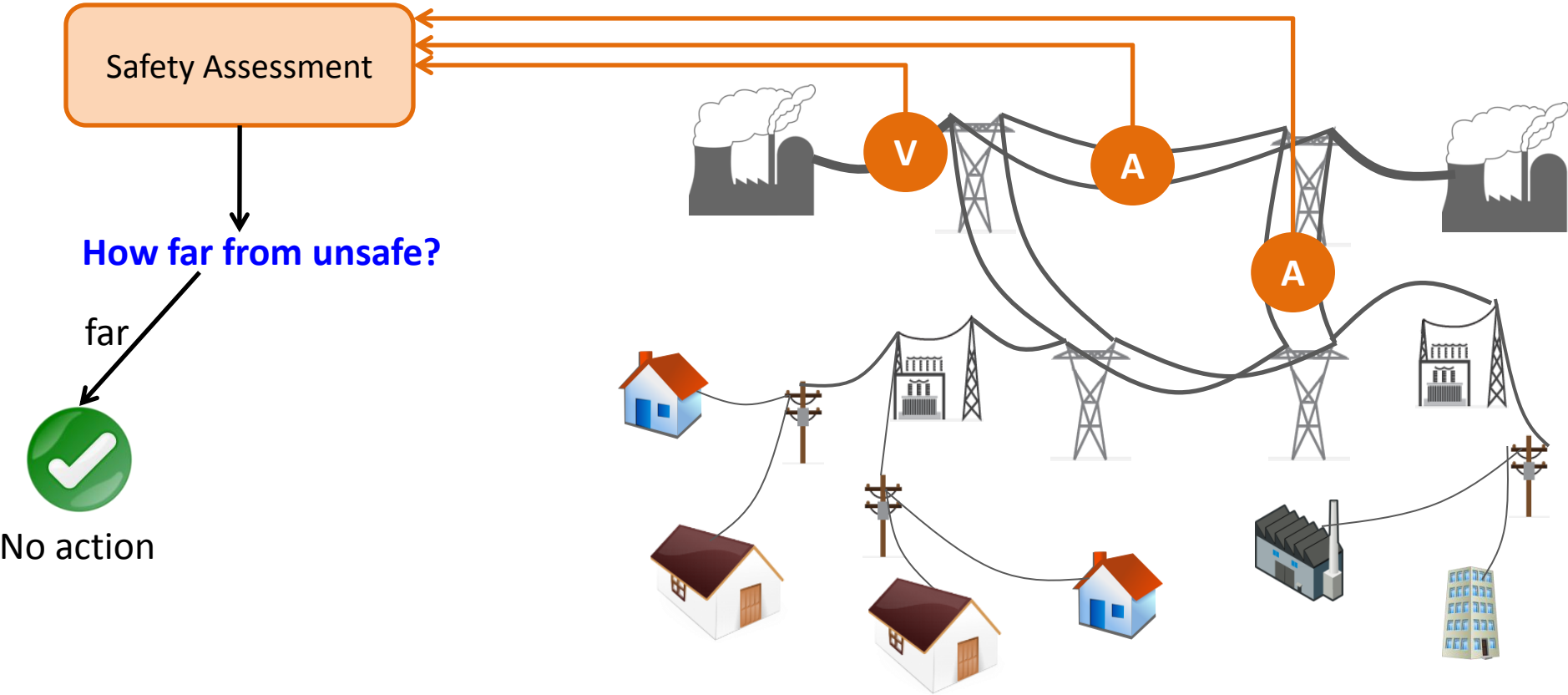
- Collaborative load curtailment
  - Fair, less painful
  - Untrustworthy (human factors, huge # of edge devices)
- Handle overload using curtailment with safety assurance?



The screenshot shows the ComEd website. The text explains that managing energy bills depends on smart choices about energy usage. It mentions that customers on ComEd's fixed-rate service don't have information about electricity costs at different times of the day. RRTP customers do have this information and it can be used for home energy management decisions. A small image of a white air conditioner is shown. The main heading is "ComEd's Central AC Cycling (Nature First) and Load Guard". Below it, a sub-heading "ComEd's Central AC Cycling (Nature First)" is followed by text explaining that if you have central air conditioning, you can sign up for the program. This program allows ComEd to cycle your air conditioner compressor off and on during summer days when demand for electricity is highest. Your fan stays on to circulate air, so your home stays comfortable.

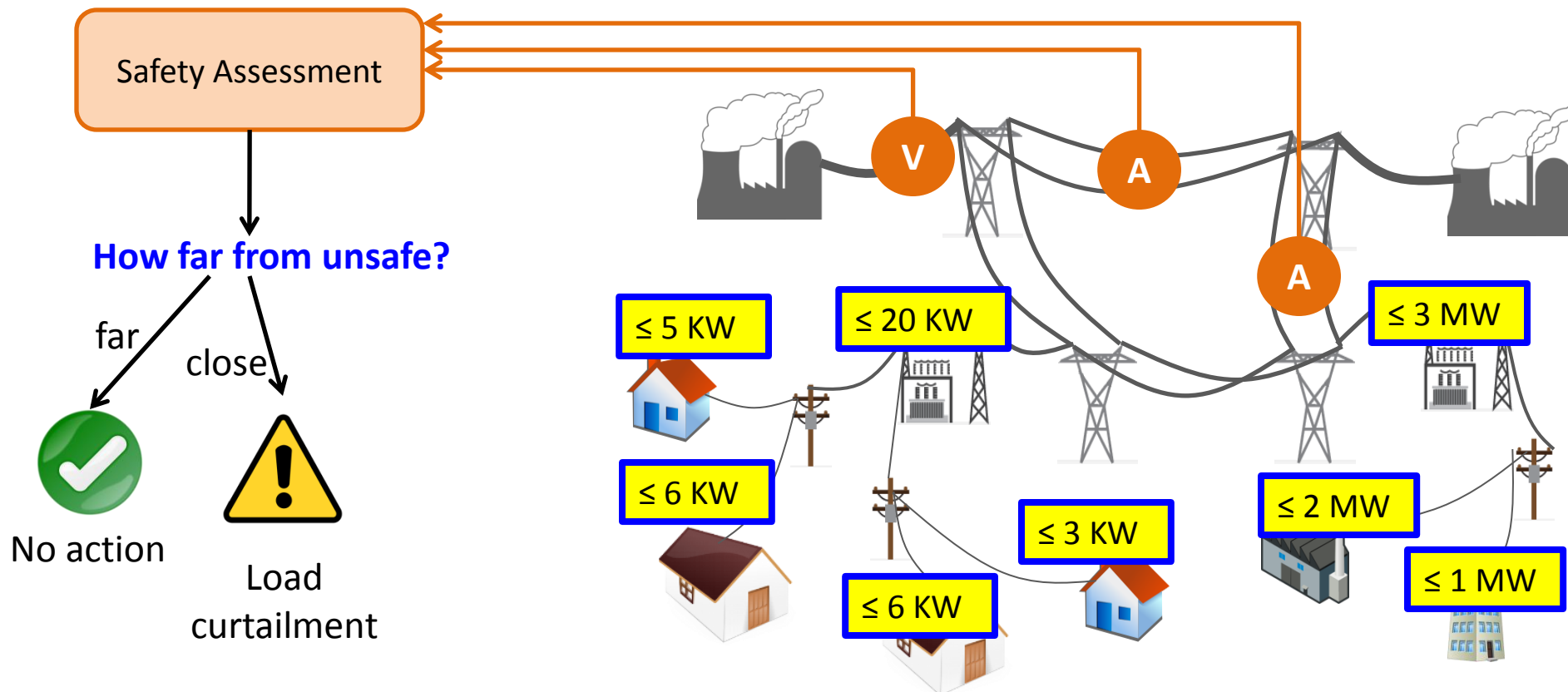
Residential air conditioner moderated by real-time electricity price [ComEd Illinois]

# Approach Overview



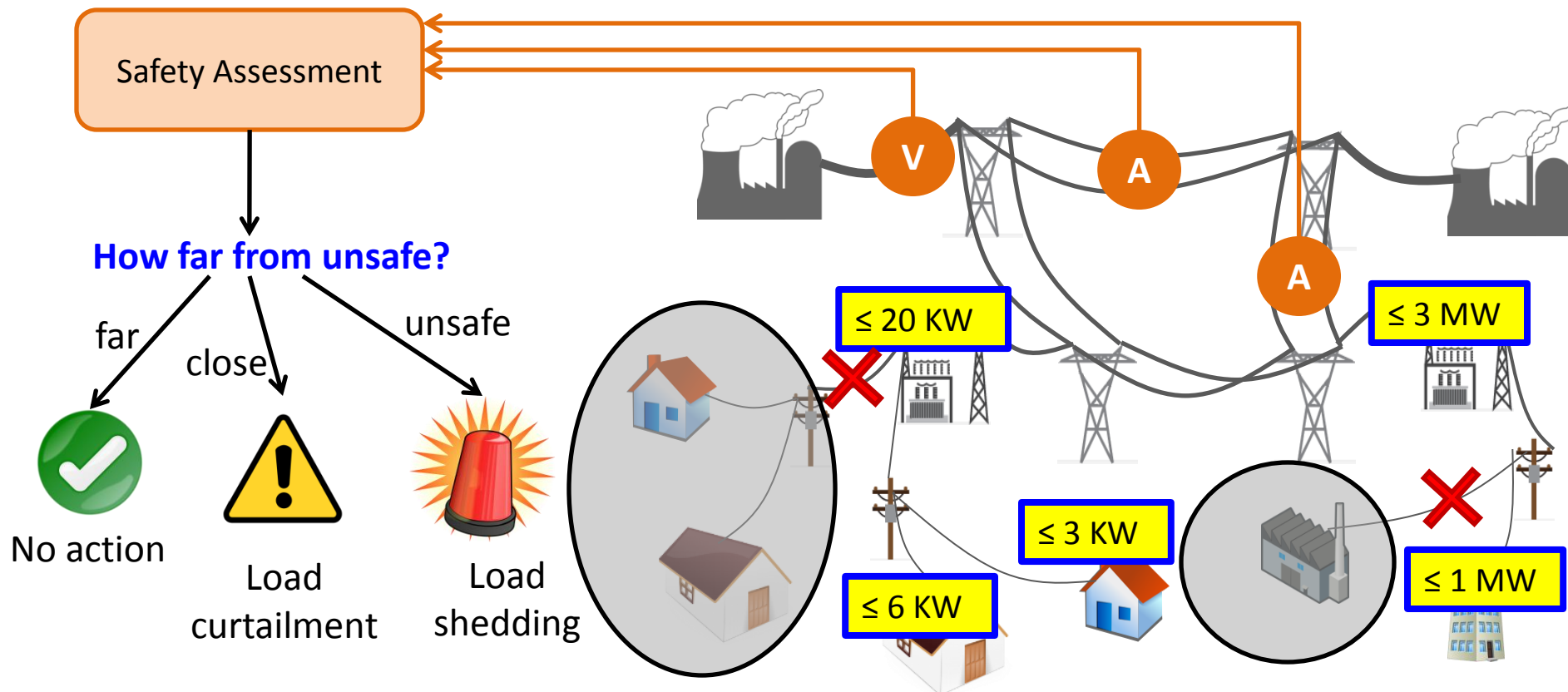
# Approach Overview

- Close to unsafe
  - Load curtailment



# Approach Overview

- Close to unsafe
  - Load curtailment
- Already unsafe
  - Load shedding



# Challenges

- Existing grid safety assessment tools
  - Time-domain simulators [PowerWorld]  
Slow!
  - Learning-based classifiers [Sun 2007, Amjady 2007]  
“Safe” or “unsafe” for triggering shedding

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  - Too late to trigger curtailment if already unsafe
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  - Learning-based classifiers [Sun 2007, Amjady 2007]  
“Safe” or “unsafe” for triggering shedding
- Curtailment needs time to take effect
  - Too late to trigger curtailment if already unsafe
  - Predictive assessment needed
- Safety: non-linear
  - Curtailment scheduling repeatedly invokes assessment
  - Rapid assessment needed



# Outline

- Motivation, Approach Overview
- **Rapid and Predictive Grid Safety Assessment**
- Predictive Curtailment Scheduling
- Simulations

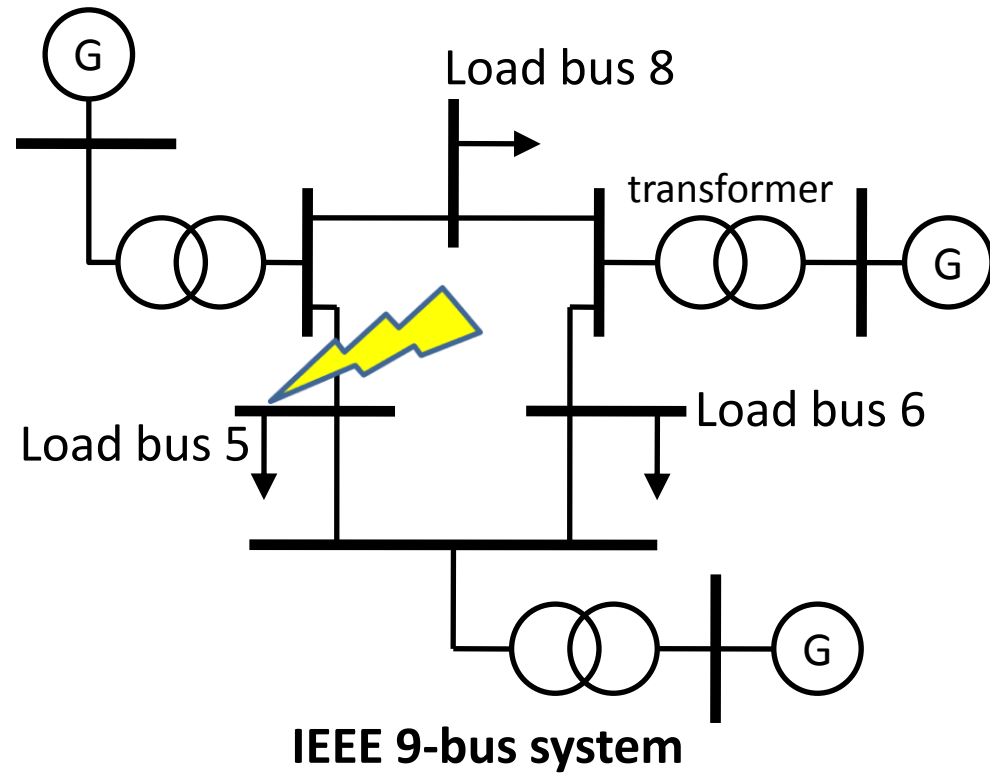
# Background of Safety Assessment

- Grid is safe if **safety condition** is met when **contingency** happens
  - Safety condition
    - Example: All generators' speed within (55 Hz, 62 Hz)
  - Contingency
    - Example 1: Most overloaded line trips
    - Example 2: Any single line trips
- Safety depends on grid state
  - Load (dominating)

# Background of Safety Assessment

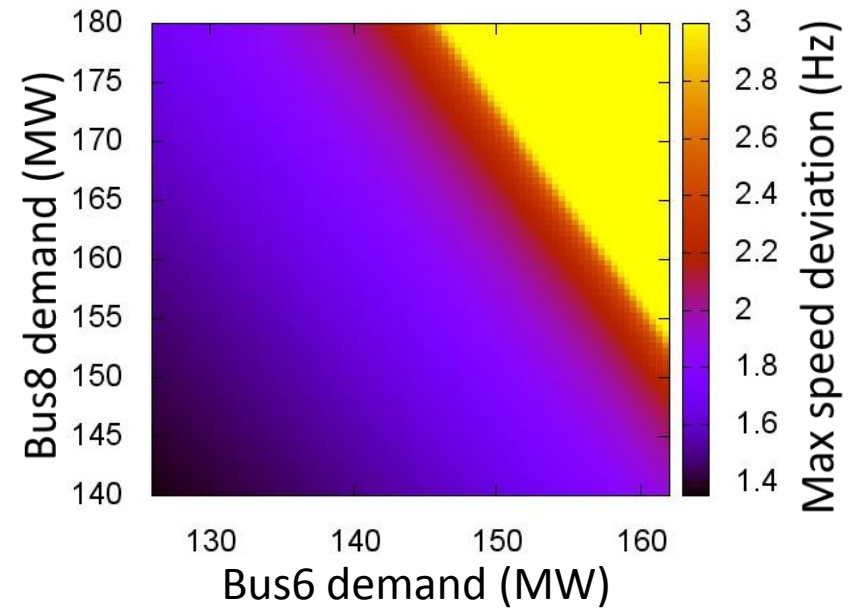
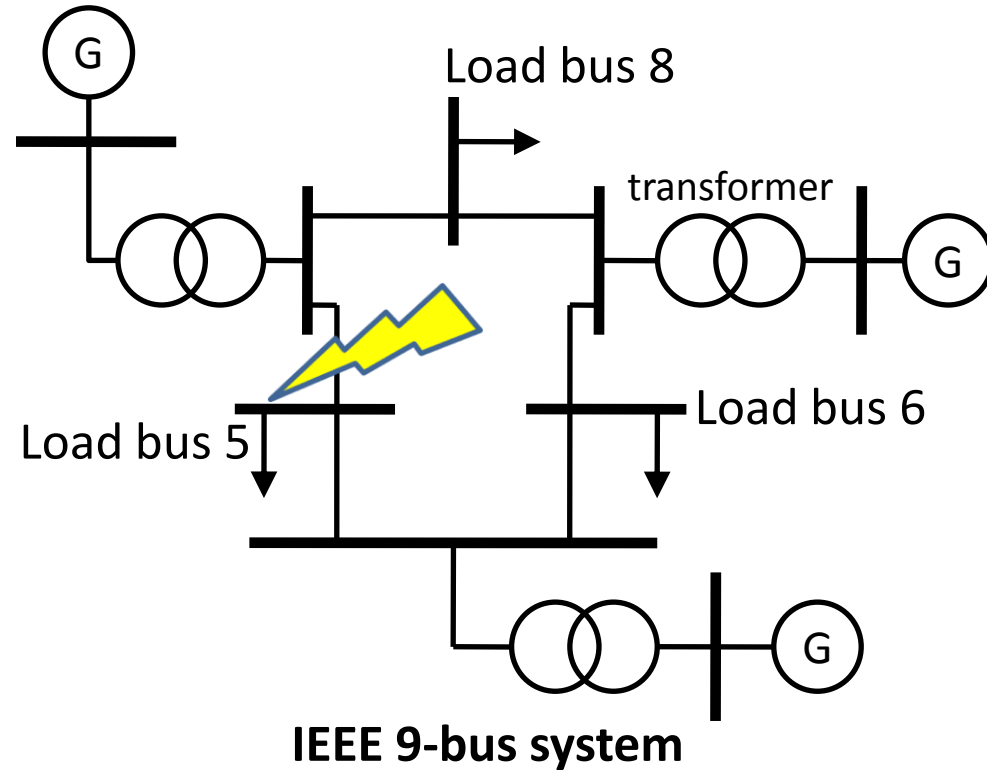
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  - Safety depends on grid state
    - Load (dominating)
- Basic requirement: Tolerate loss of any single line

# An Example



- Safety assessment
  - Contingency: short circuit on a line

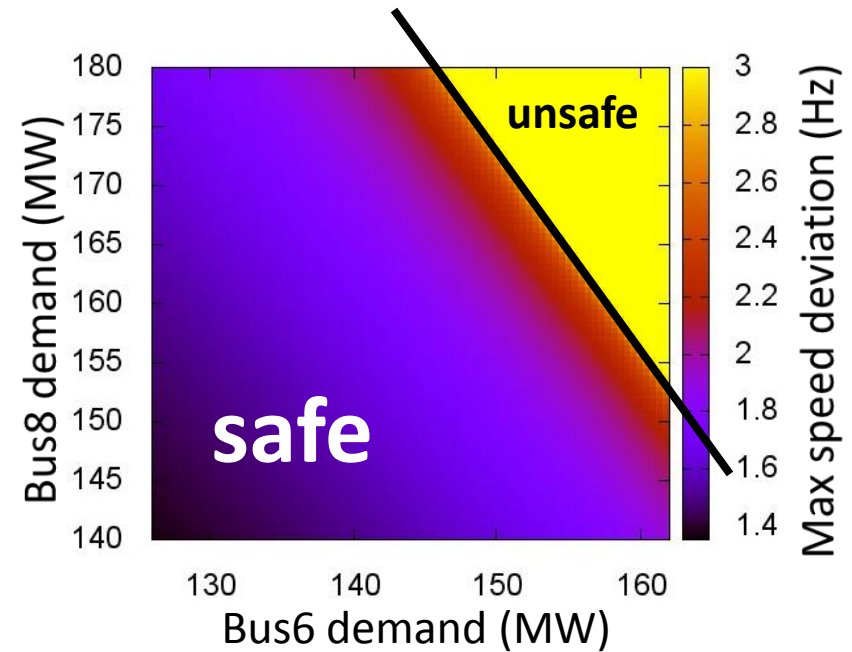
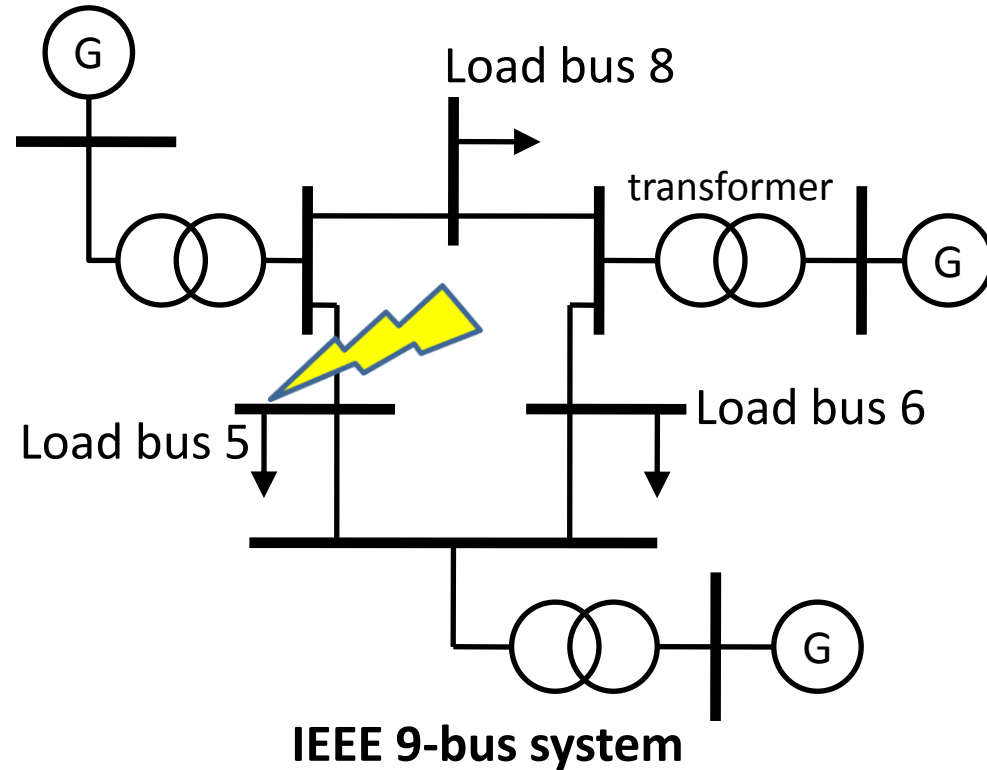
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**Time-domain simulation result**  
(Bus5 demand fixed)

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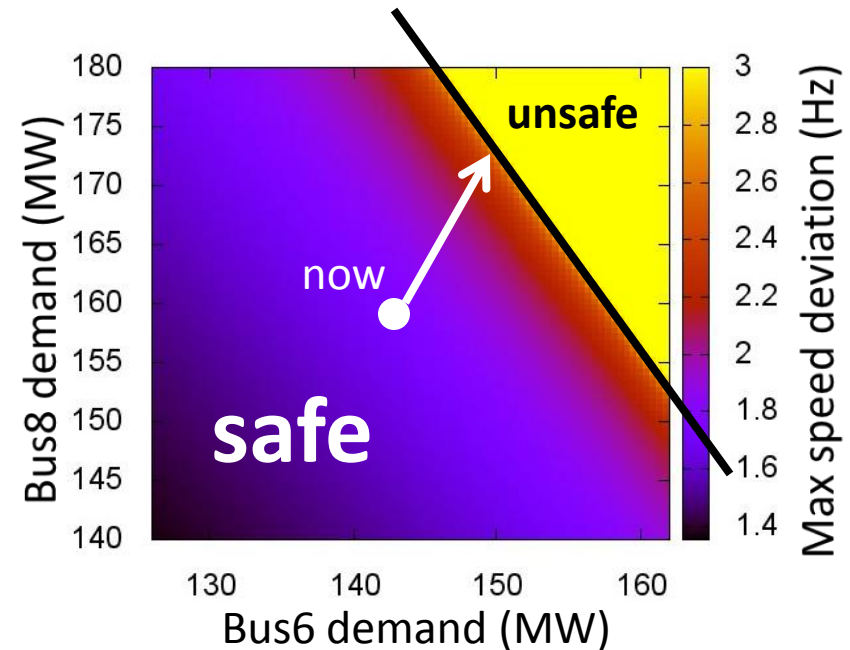
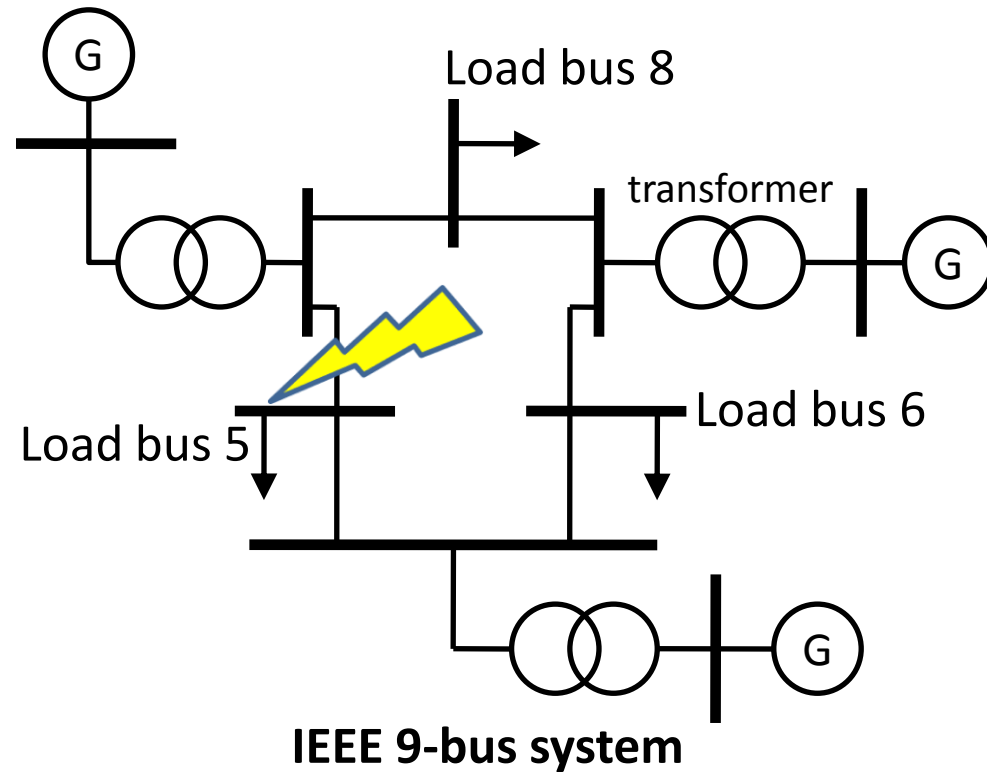
# An Example



**Time-domain simulation result**  
(Bus5 demand fixed)

- Safety assessment
  - Contingency: short circuit on a line
  - Safety condition: speed dev < 3 Hz

# An Example



**Time-domain simulation result**  
(Bus5 demand fixed)

- Safety assessment
  - Contingency: short circuit on a line
  - Safety condition: speed dev < 3 Hz
- A grid becomes unsafe if demands increase
  - How much time from now?

# Time to Being Unsafe (TTBU)

- TTBU is minimum time  $t$   
grid with demand  $\mathbf{D} + \Delta(t)$  is unsafe

vector of buses'  
demands

max demand  
increment over  
time period  $t$

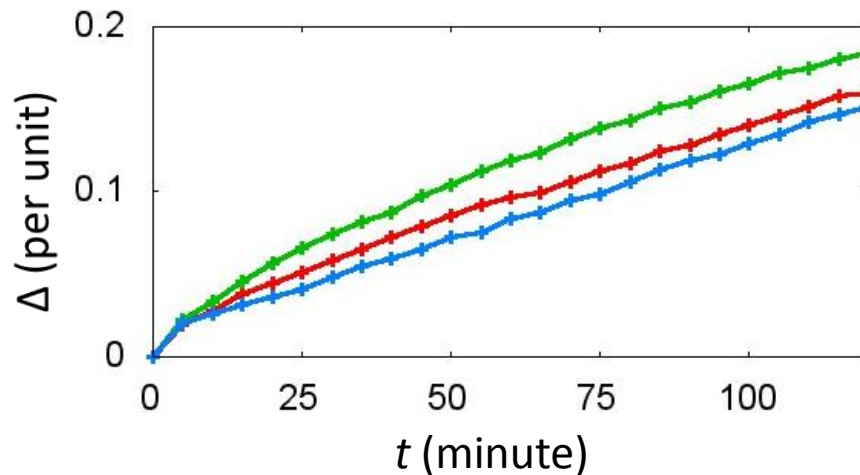


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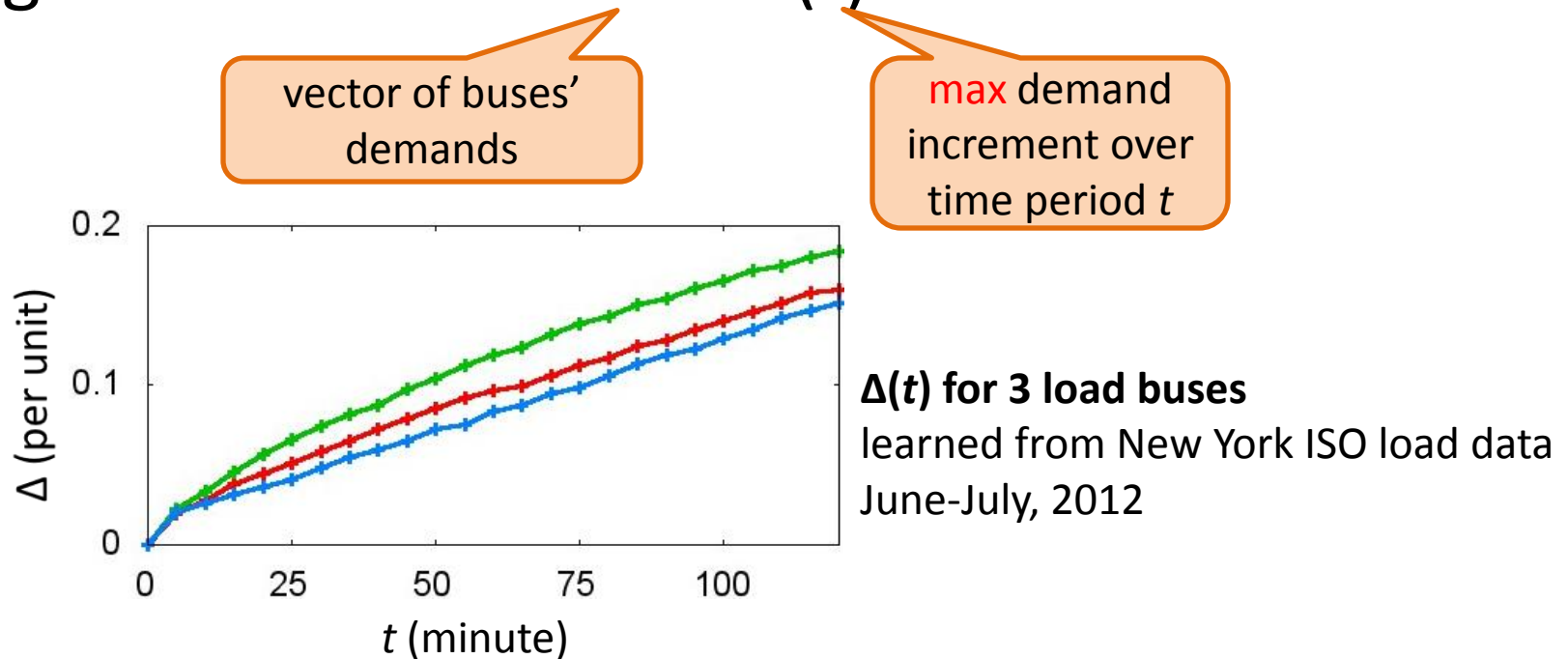


$\Delta(t)$  for 3 load buses

learned from New York ISO load data  
June-July, 2012

# Time to Being Unsafe (TTBU)

- TTBU is minimum time  $t$  grid with demand  $\mathbf{D} + \Delta(t)$  is unsafe



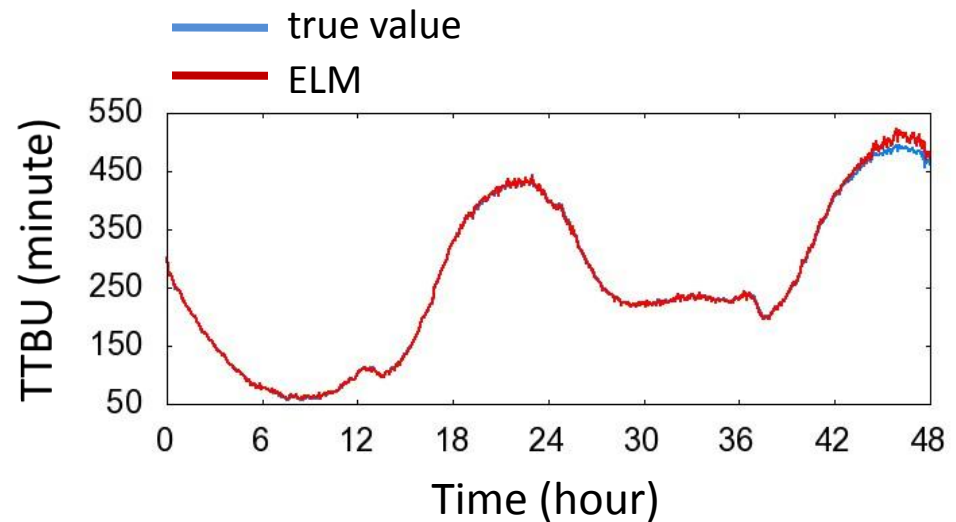
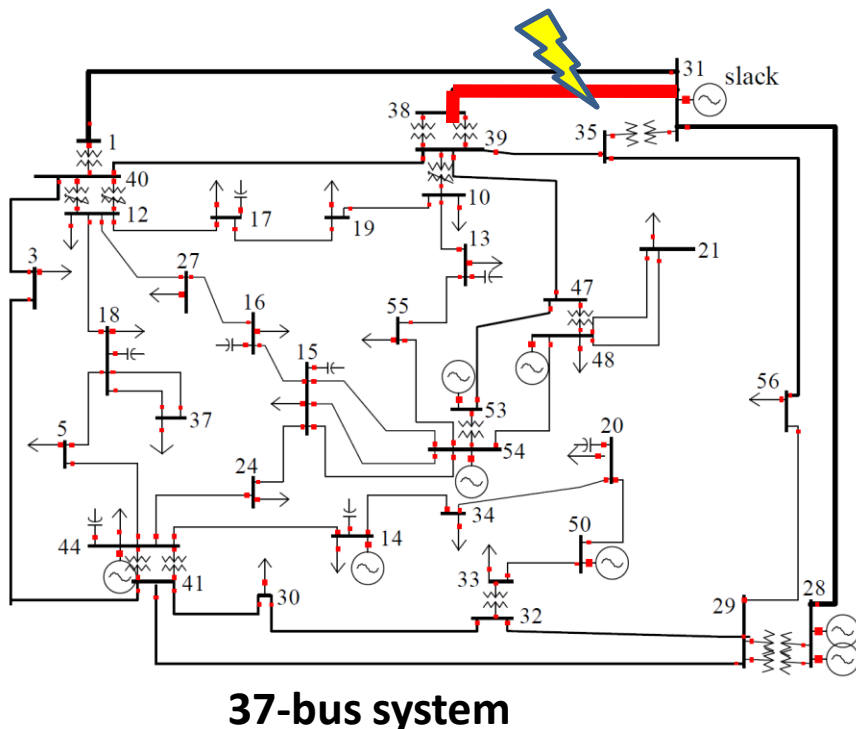
- **Predictive** but **compute-intensive** safety metric
  - Run PowerWorld for each  $t$   
*15 secs for 37-bus system on 4core @ 2.8GHz*

# ELM-Based Assessment

- Extreme Learning Machine [Huang 2006]
  - Neural network with one hidden layer
- Training data set {<demand vector, TTBU>}
  - Demand history
  - TTBU from offline time-domain simulations

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avg err = 0.9%  
 $10^5$ x speed-up

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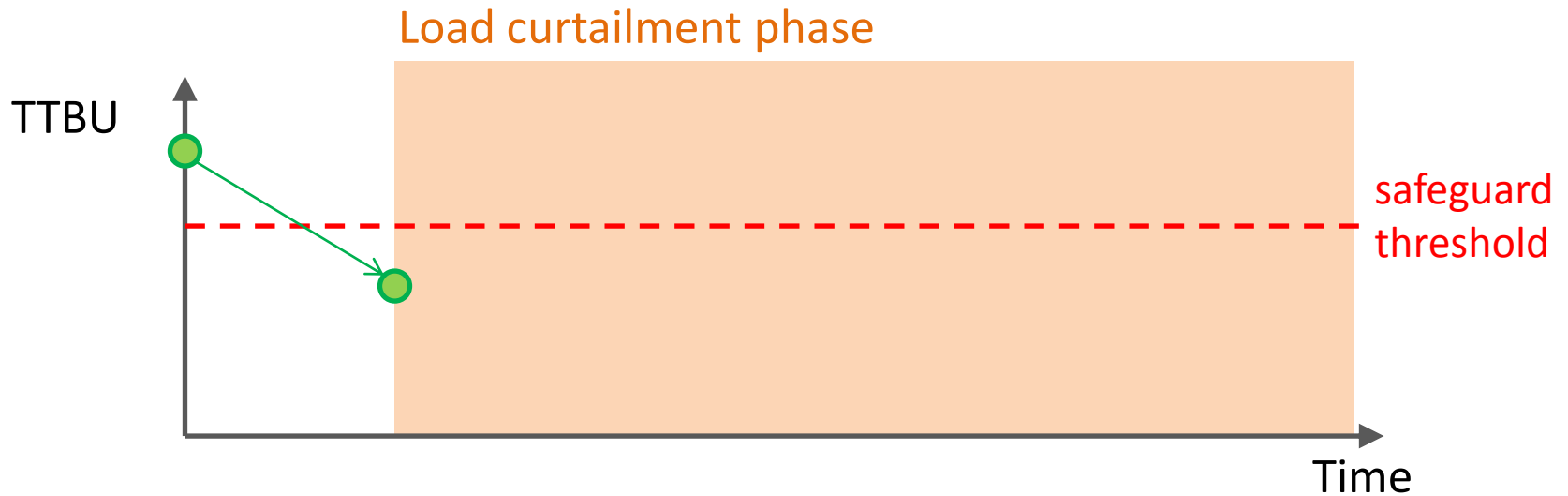
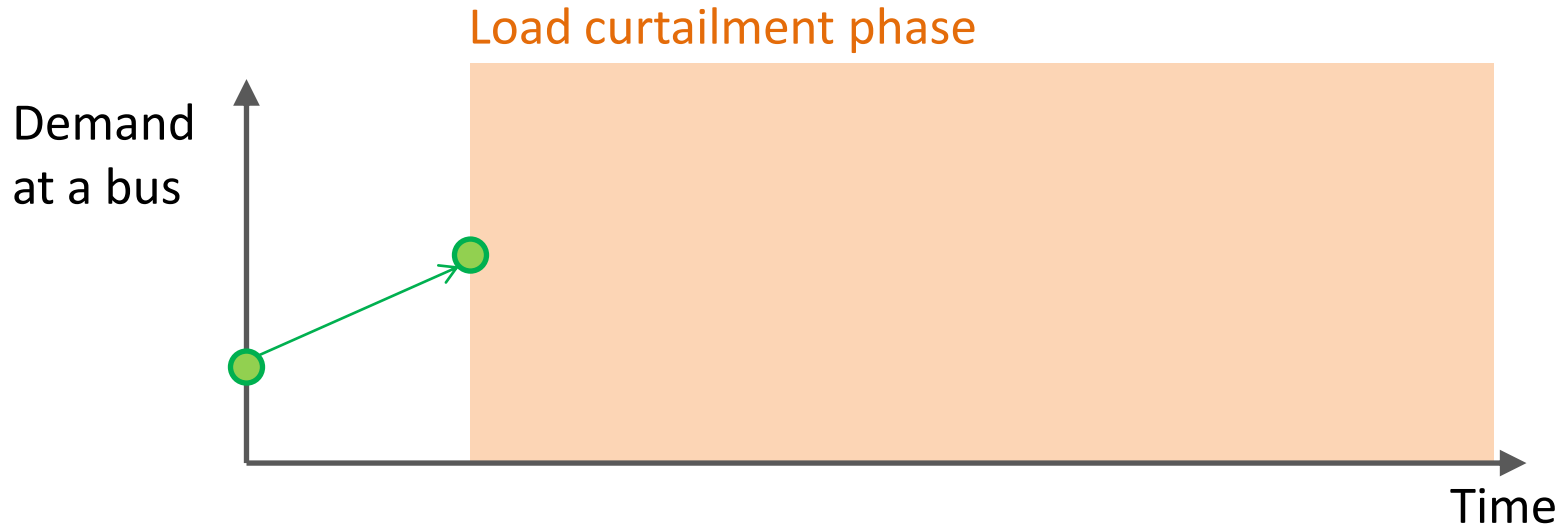
# Load Curtailment Scheme



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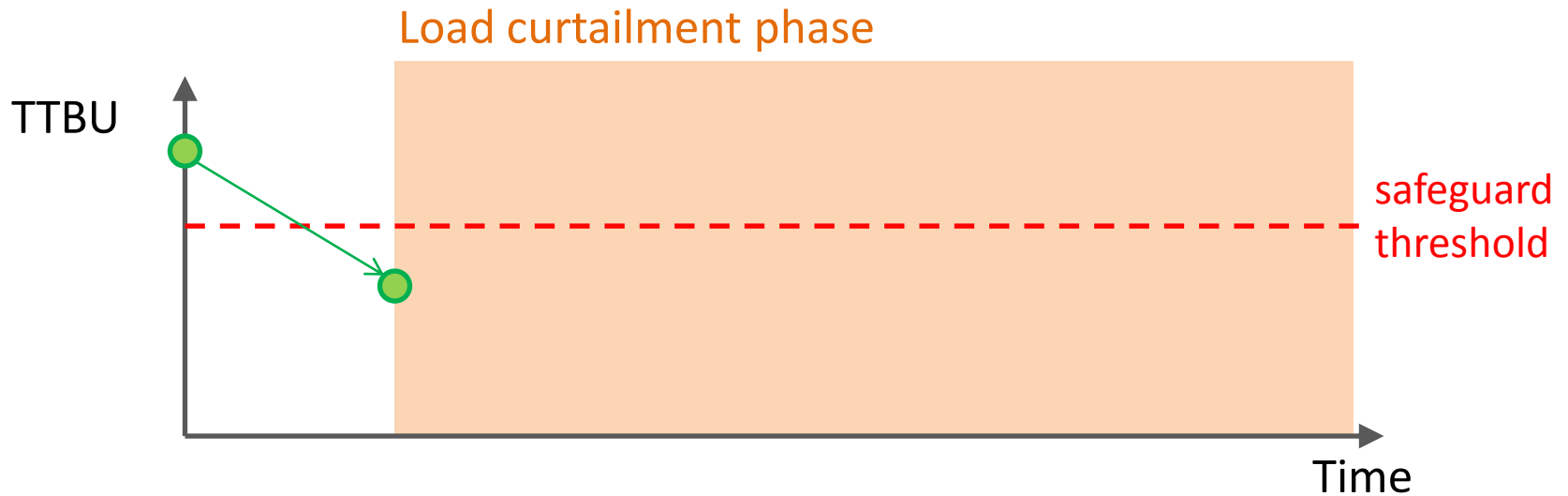
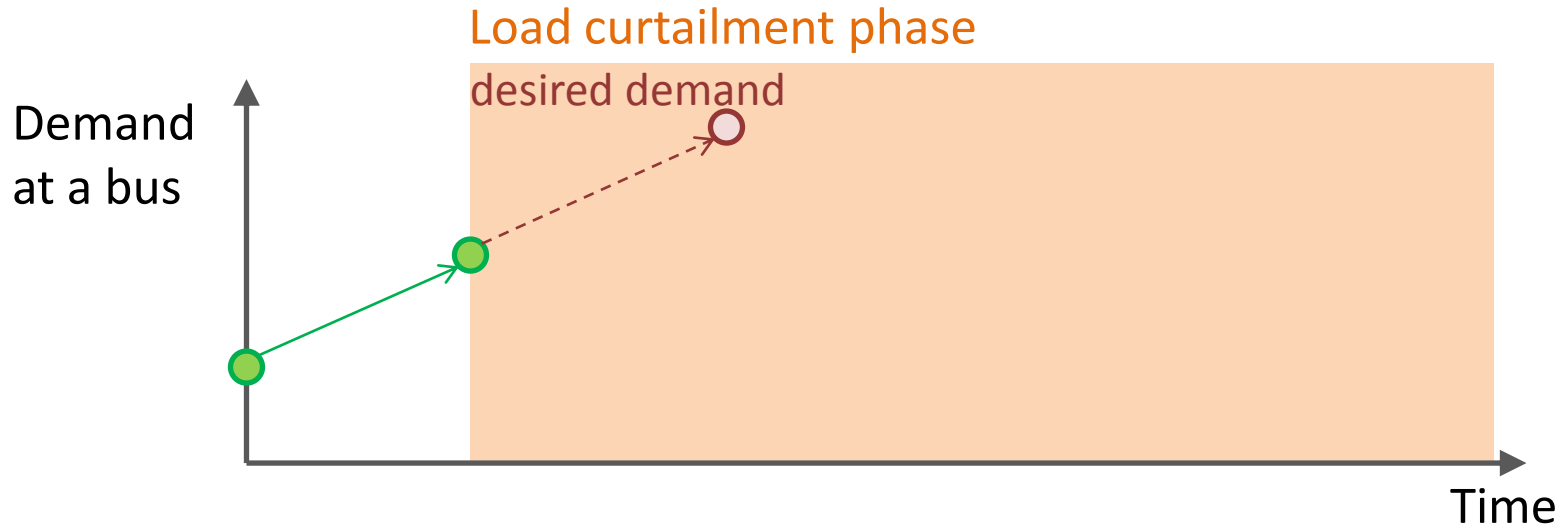


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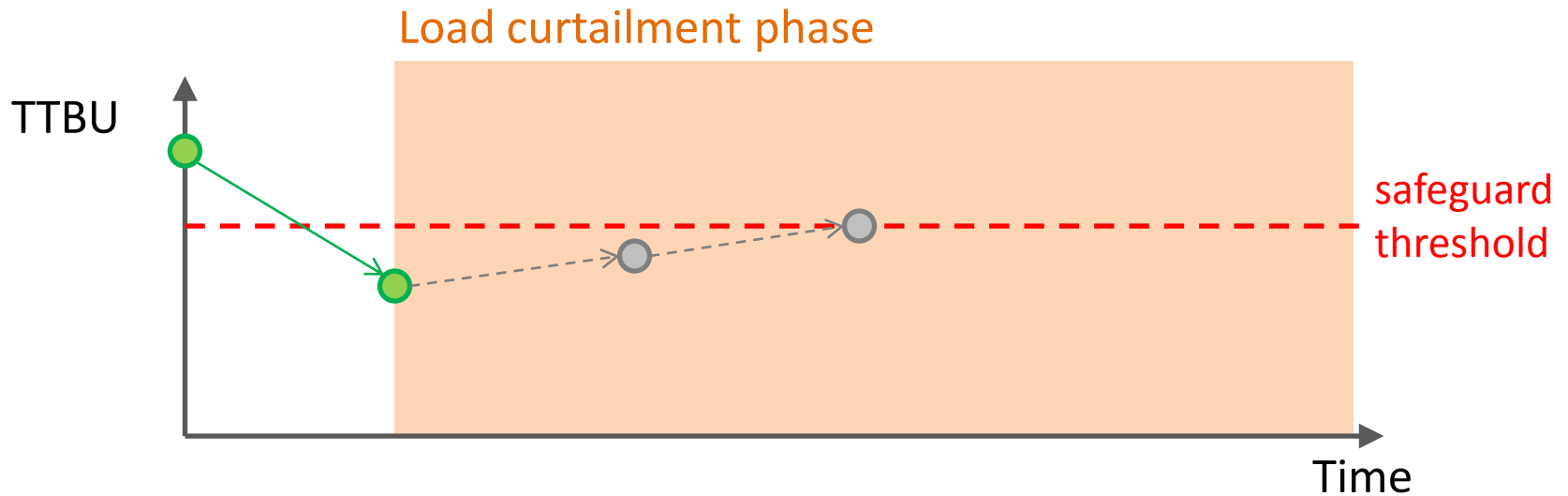
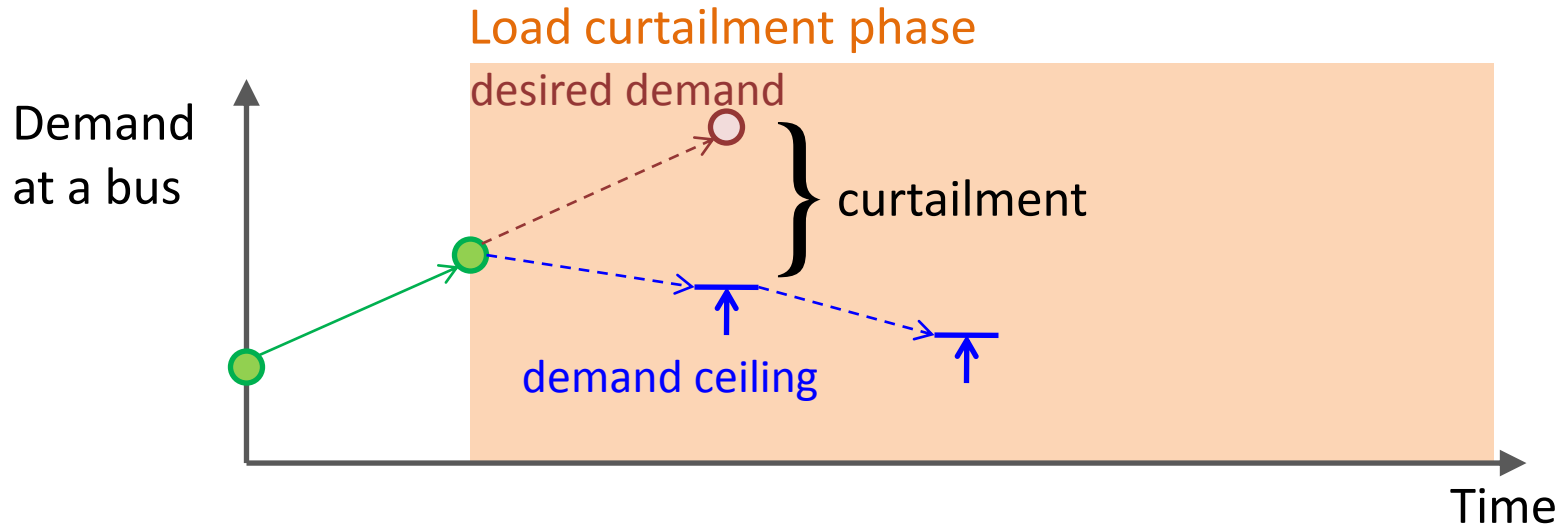




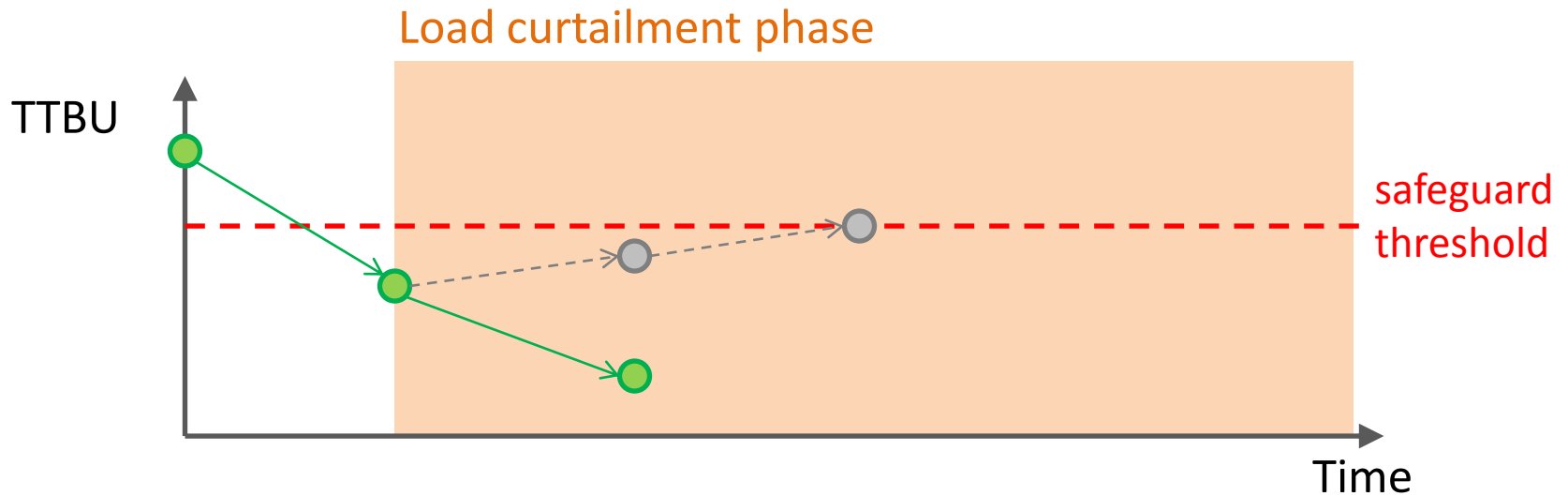
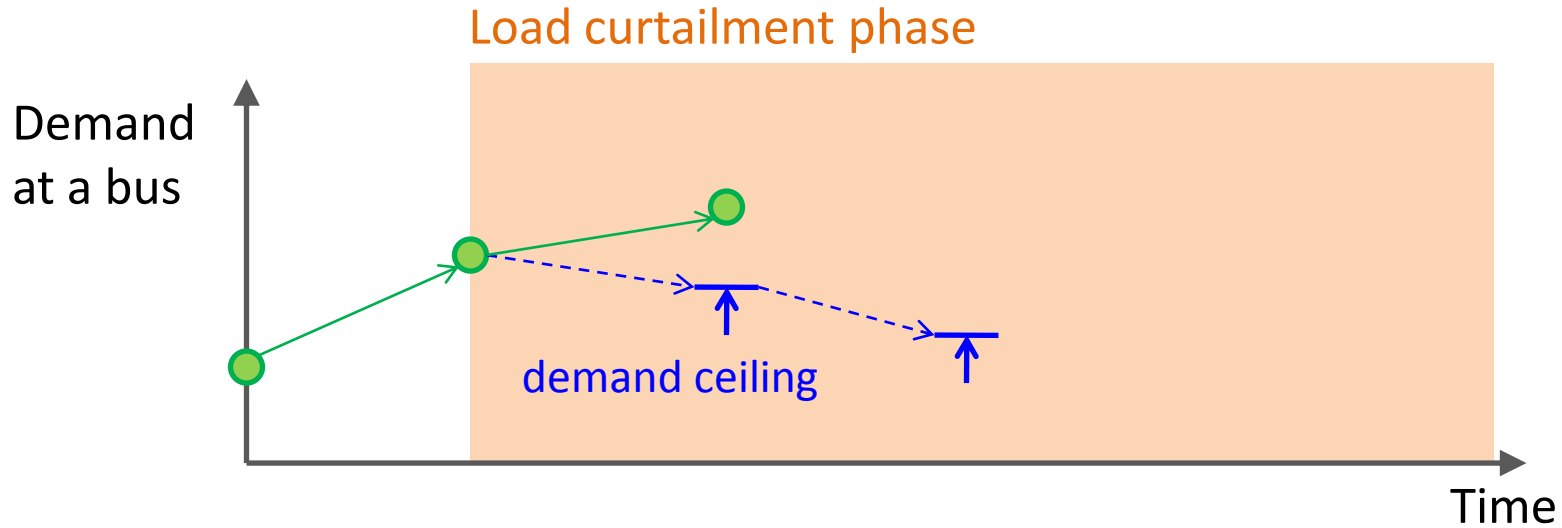
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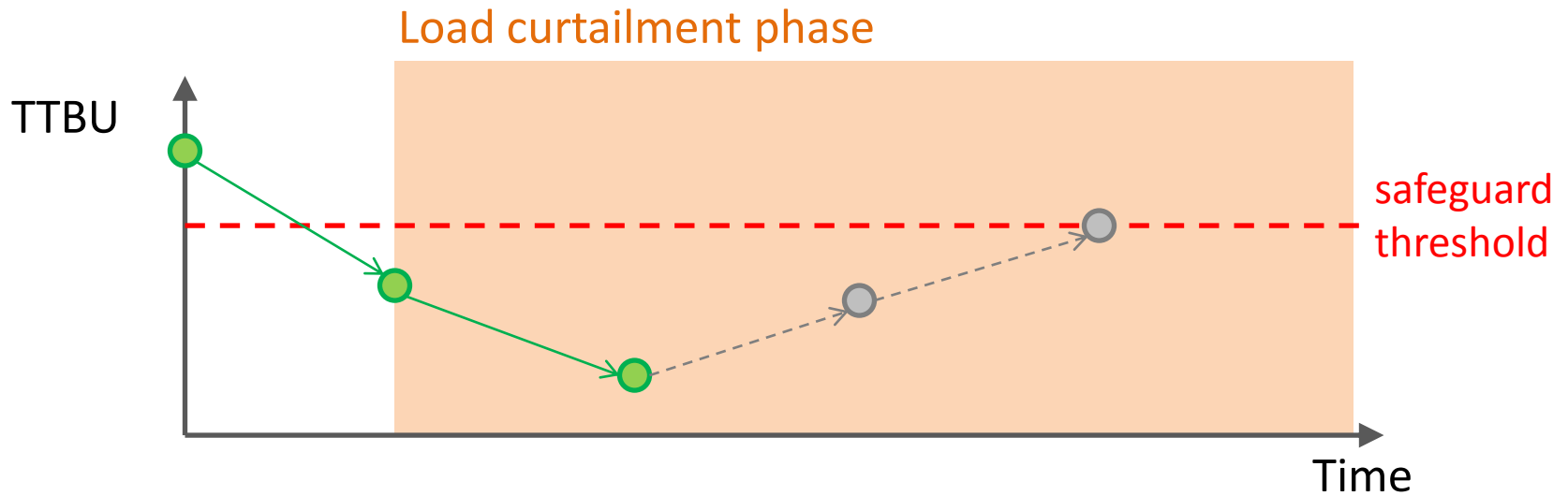
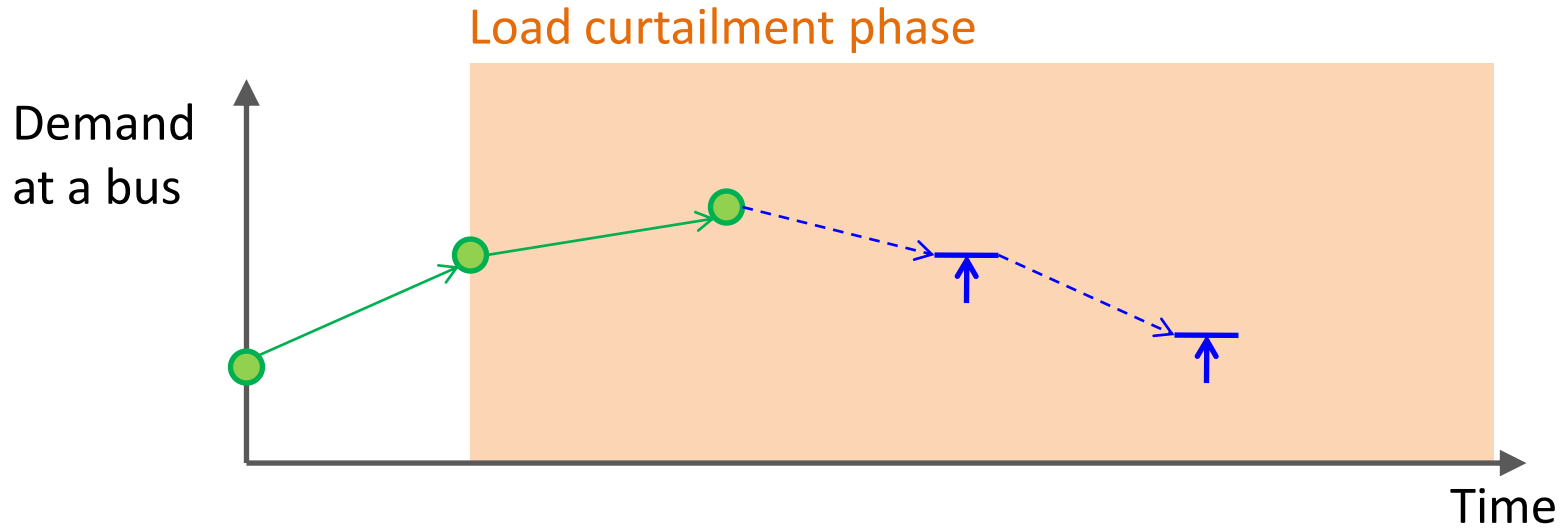
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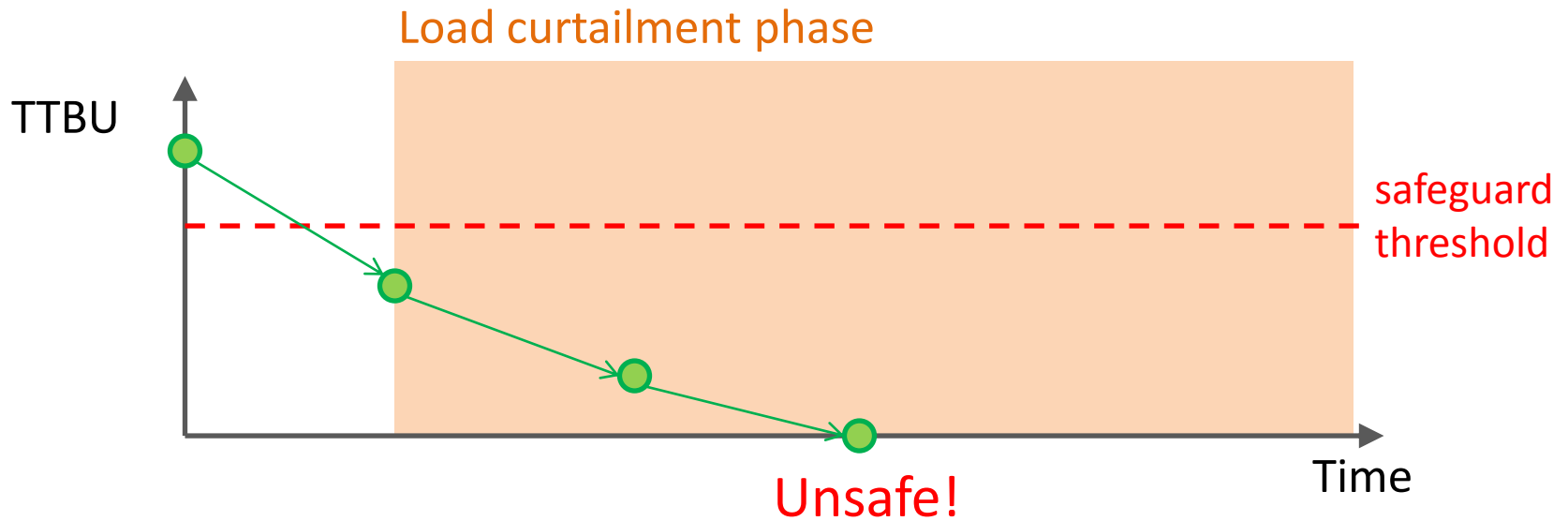
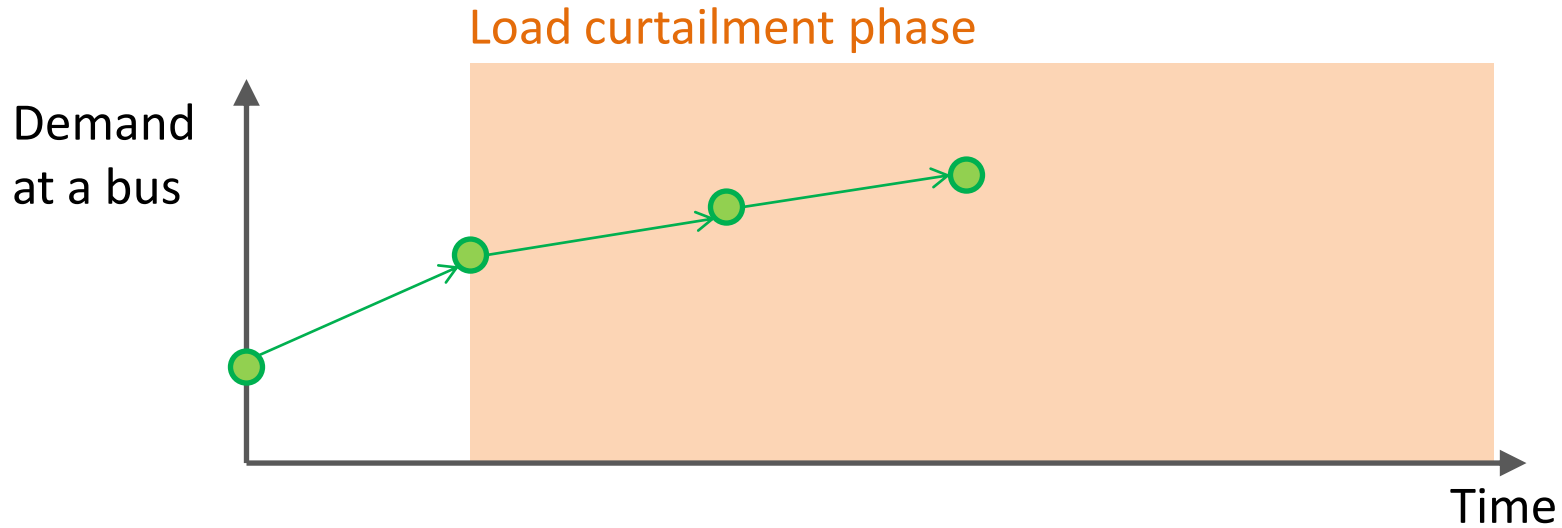
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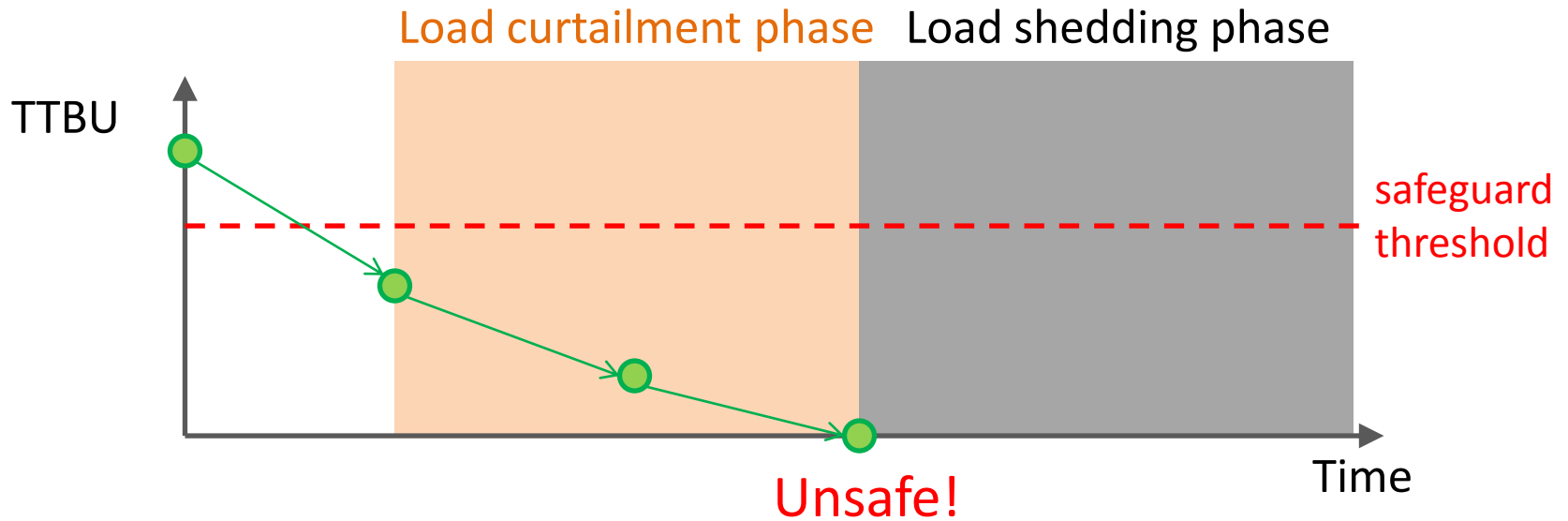
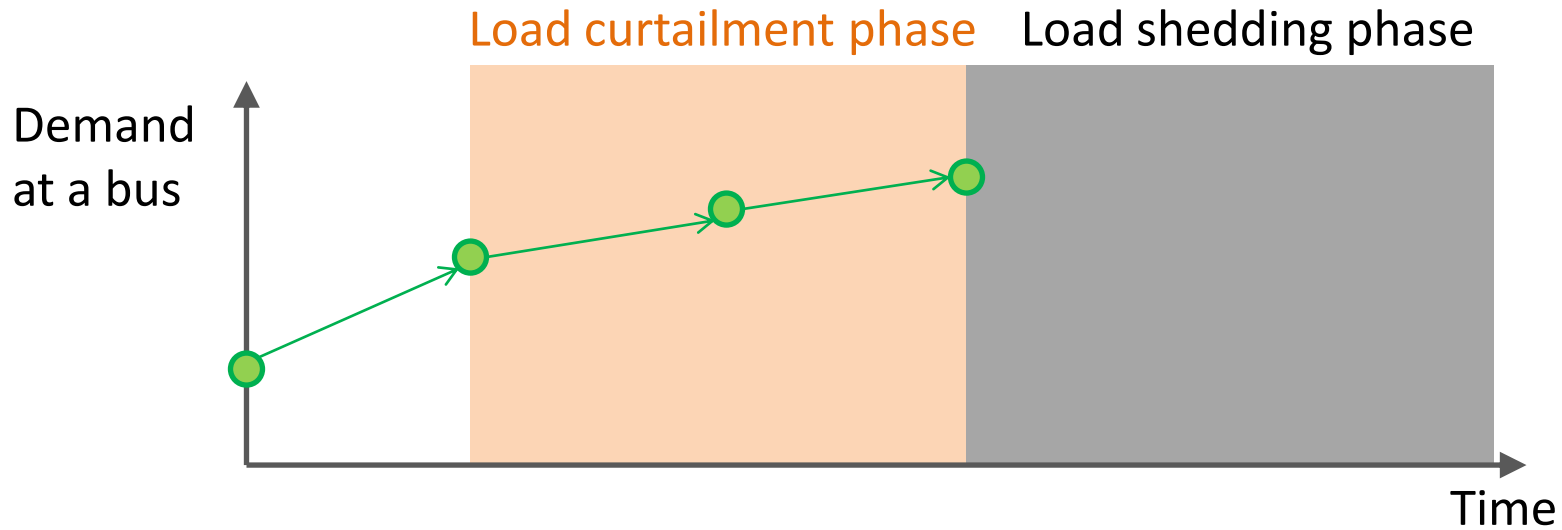
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- Strong temporal correlation
  - One-step prediction

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$$\hat{d}_h = f(\hat{d}_{h-1}, \dots, \hat{d}_1, d_0, \dots, d_{-R+h})$$



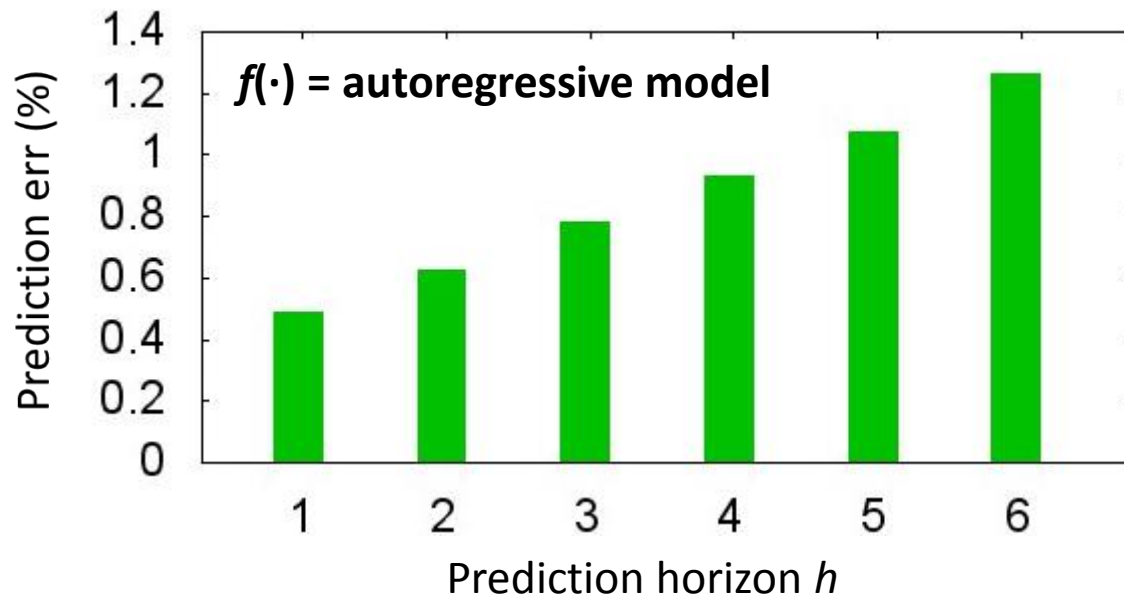
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New York ISO data  
Cycle = 10 min  
R = 12

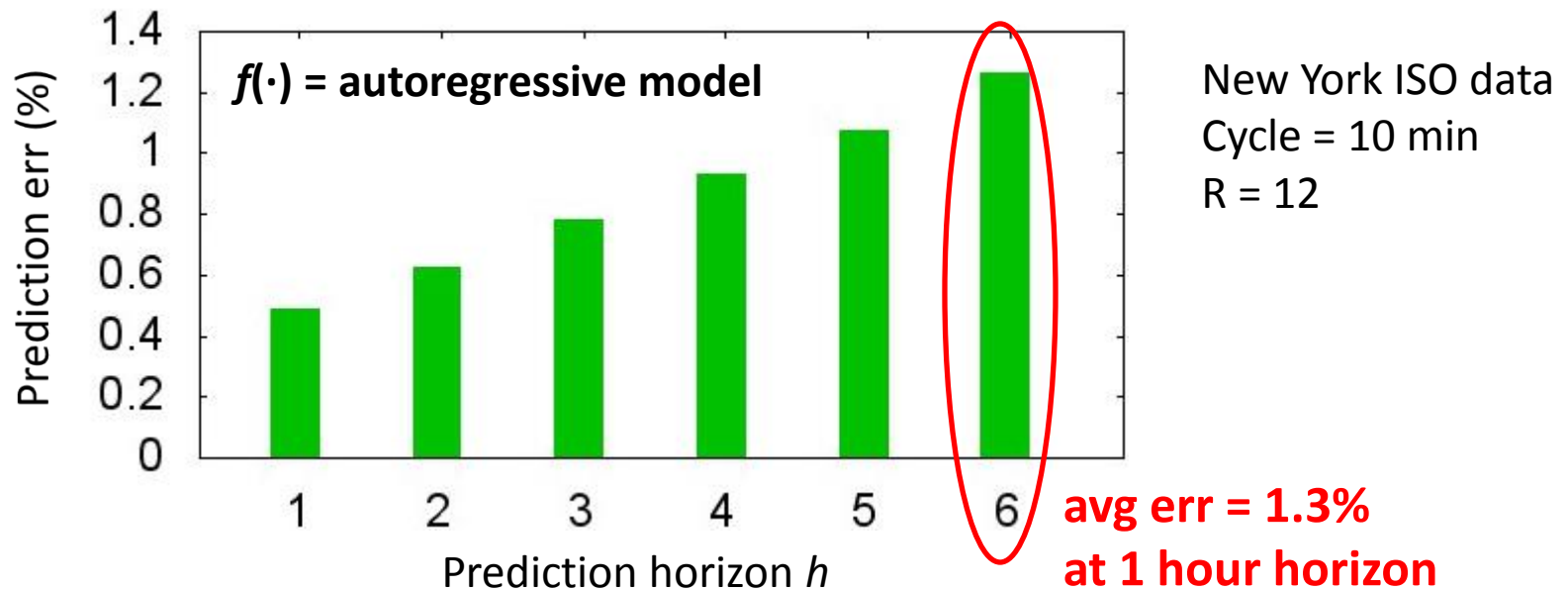
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# Curtailment Scheduling

- Find curtailments  $\{x_1, x_2, \dots, x_H\}$

$$\text{min.} \quad \sum_{h=1}^H |\mathbf{TTBU}_h - \mathbf{safeguard}|$$

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Predicted TTBU at horizon  $h$

ELM

Demand ceiling  
at horizon  $h$

$$\hat{d}_h = f(\hat{d}_{h-1}, \dots, \hat{d}_1, d_0, \dots, d_{-R+h}) - x_h$$

Predicted demand at horizon  $h$

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$$\sigma(x_1, x_2, \dots, x_H) \leq \sigma_0$$

Curtailments variation

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Curtailments variation

$$\sigma = \max_{h=1}^H | x_h - x_{h-1} |$$

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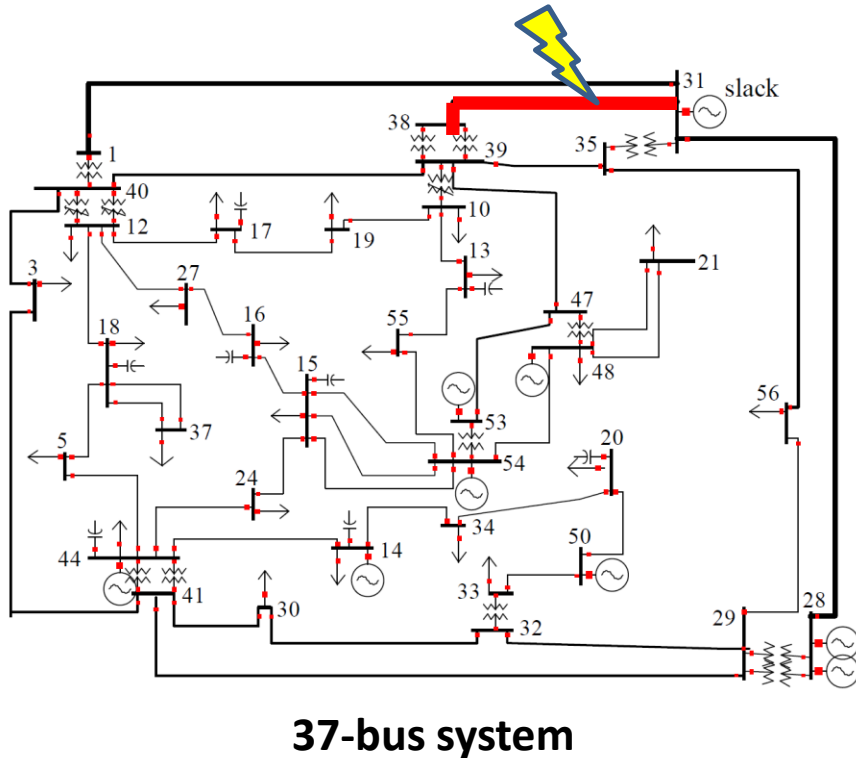
Curtailments variation

optional

$$\sigma = \max_{h=1}^H | x_h - x_{h-1} |$$



# Simulation Settings



## Contingency:

Short circuit on a backbone line

## Safety condition:

Generators' speed within (55 Hz, 62 Hz)

## Demand:

Synthesized from New York ISO load data

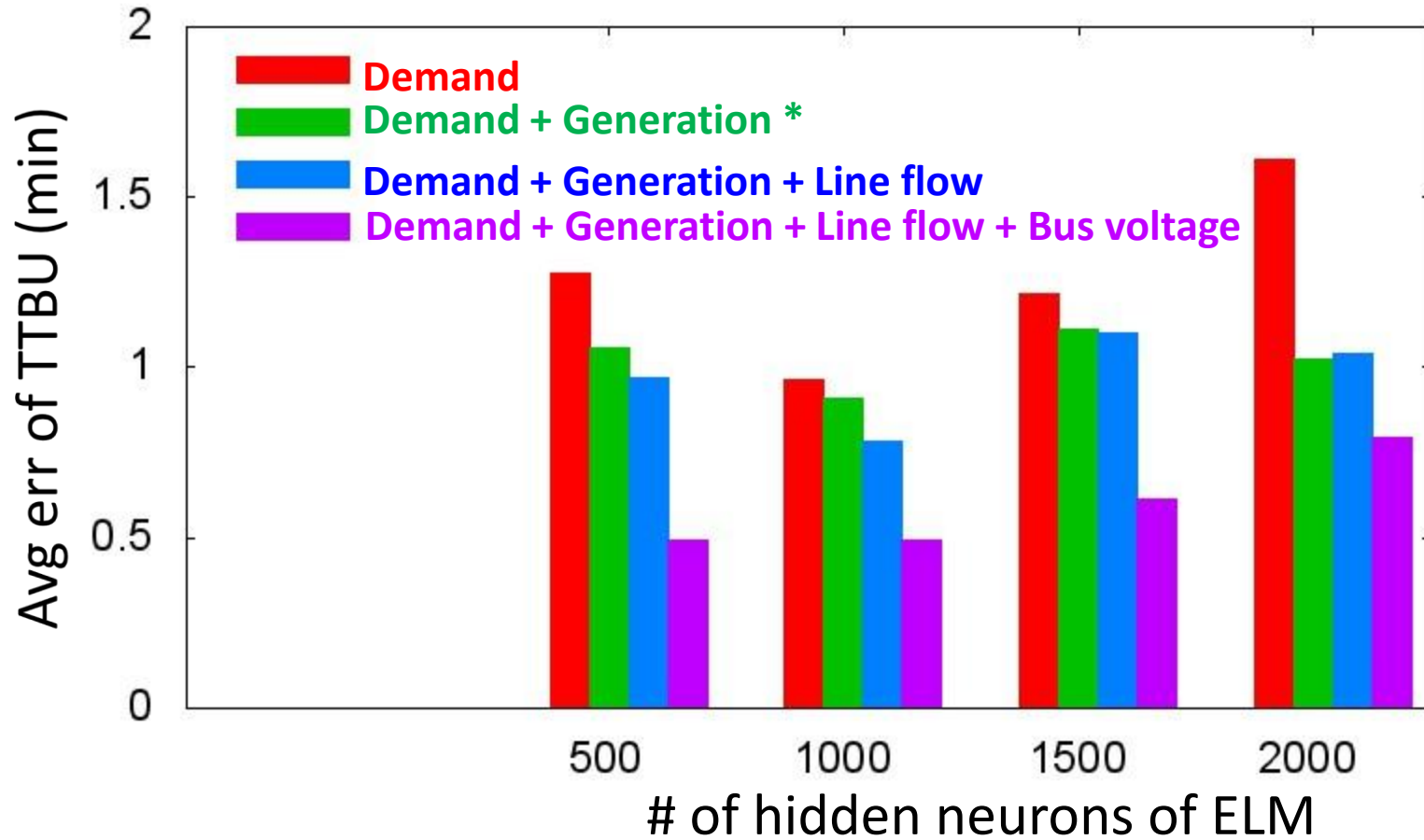
Cycle len = 10 min,  $\sigma_0 = 0.02$  p.u.

- Commitment  $\xi \in [0, 1]$

$$\text{actual demand} = \xi \times \text{demand ceiling} + (1 - \xi) \times \text{desired demand}$$

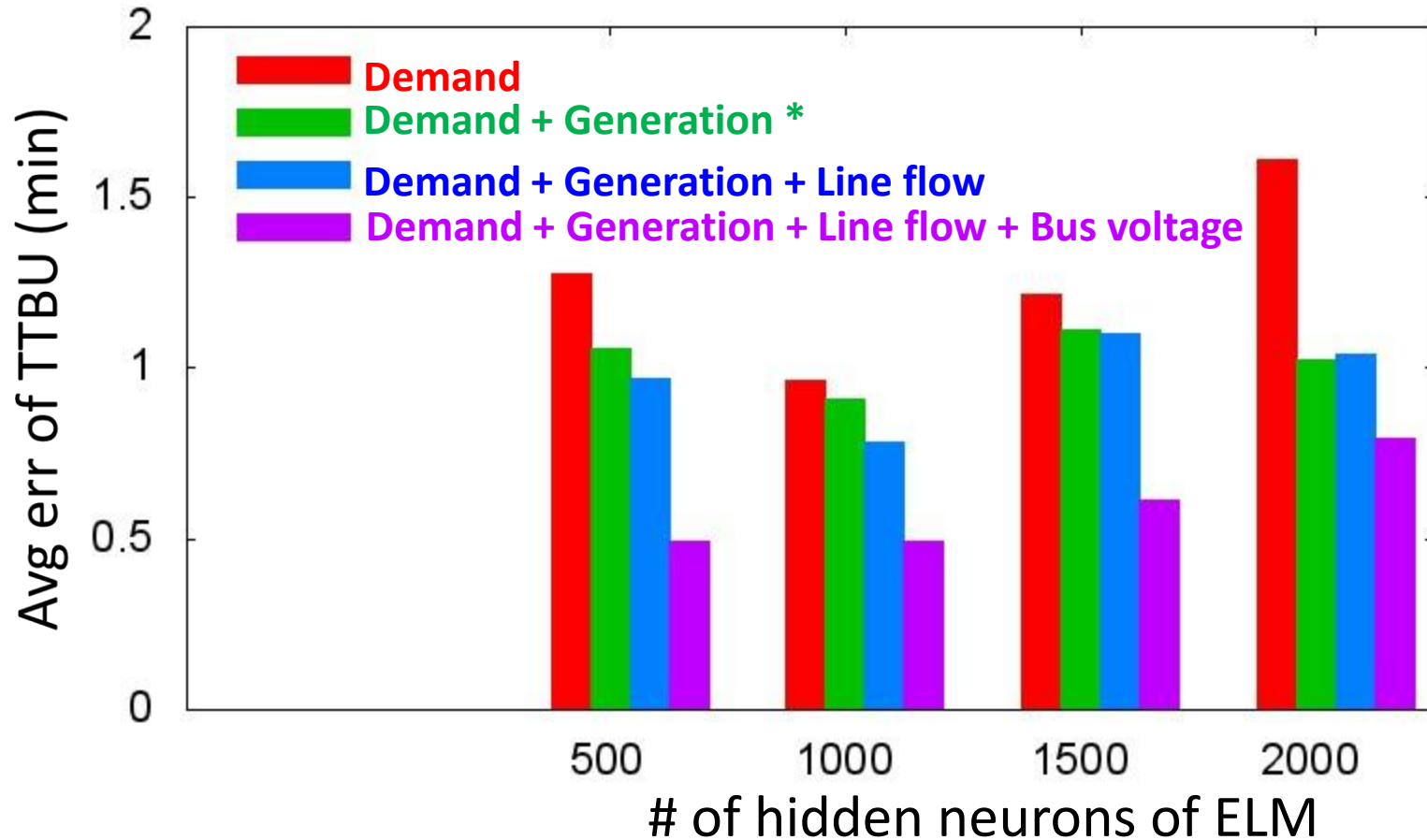
(desired demand: data traces)

# Alternative Designs of ELM



\* Generation follows demand by economic dispatch

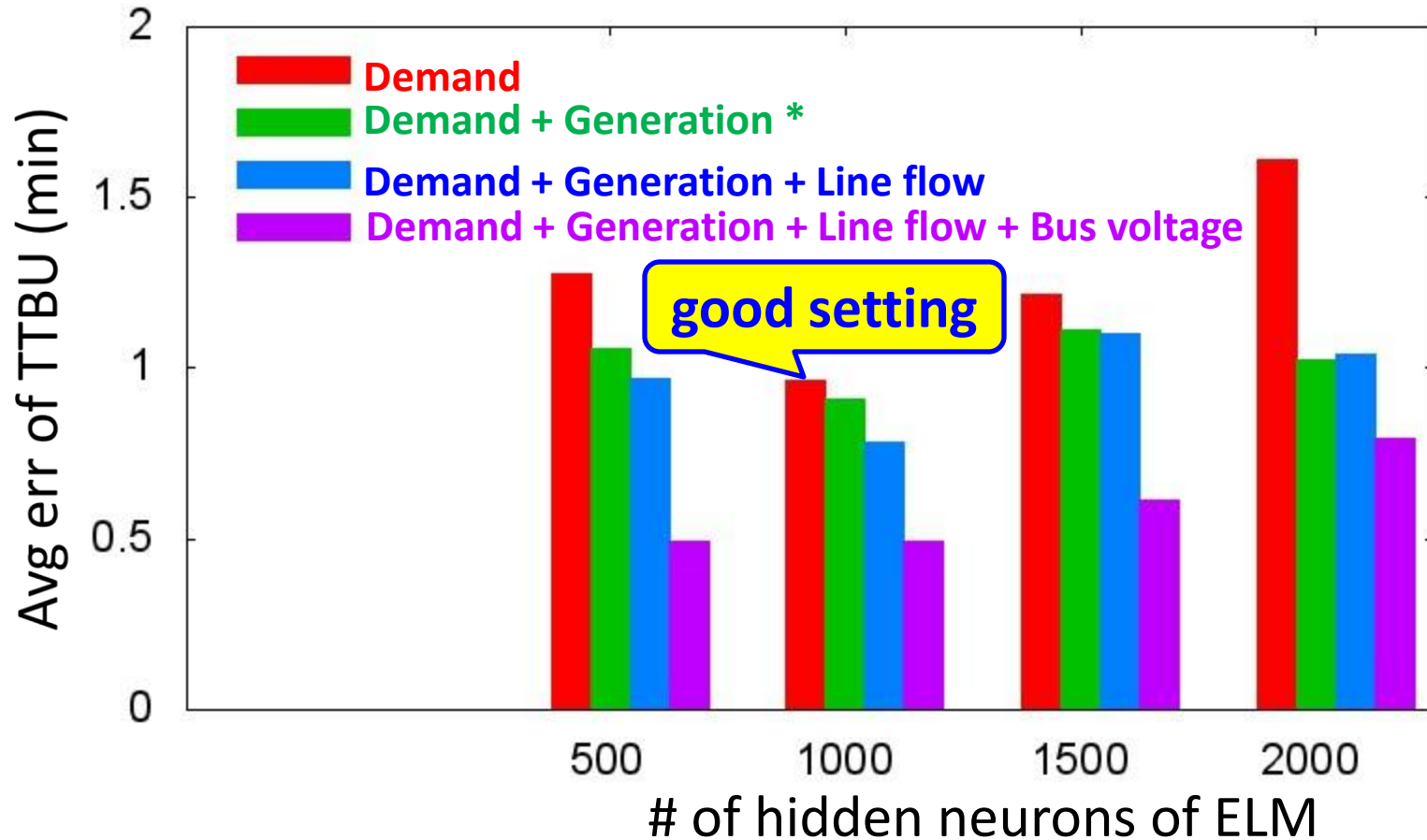
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  - Need more sensors
  - Estimating them from demands incur overhead

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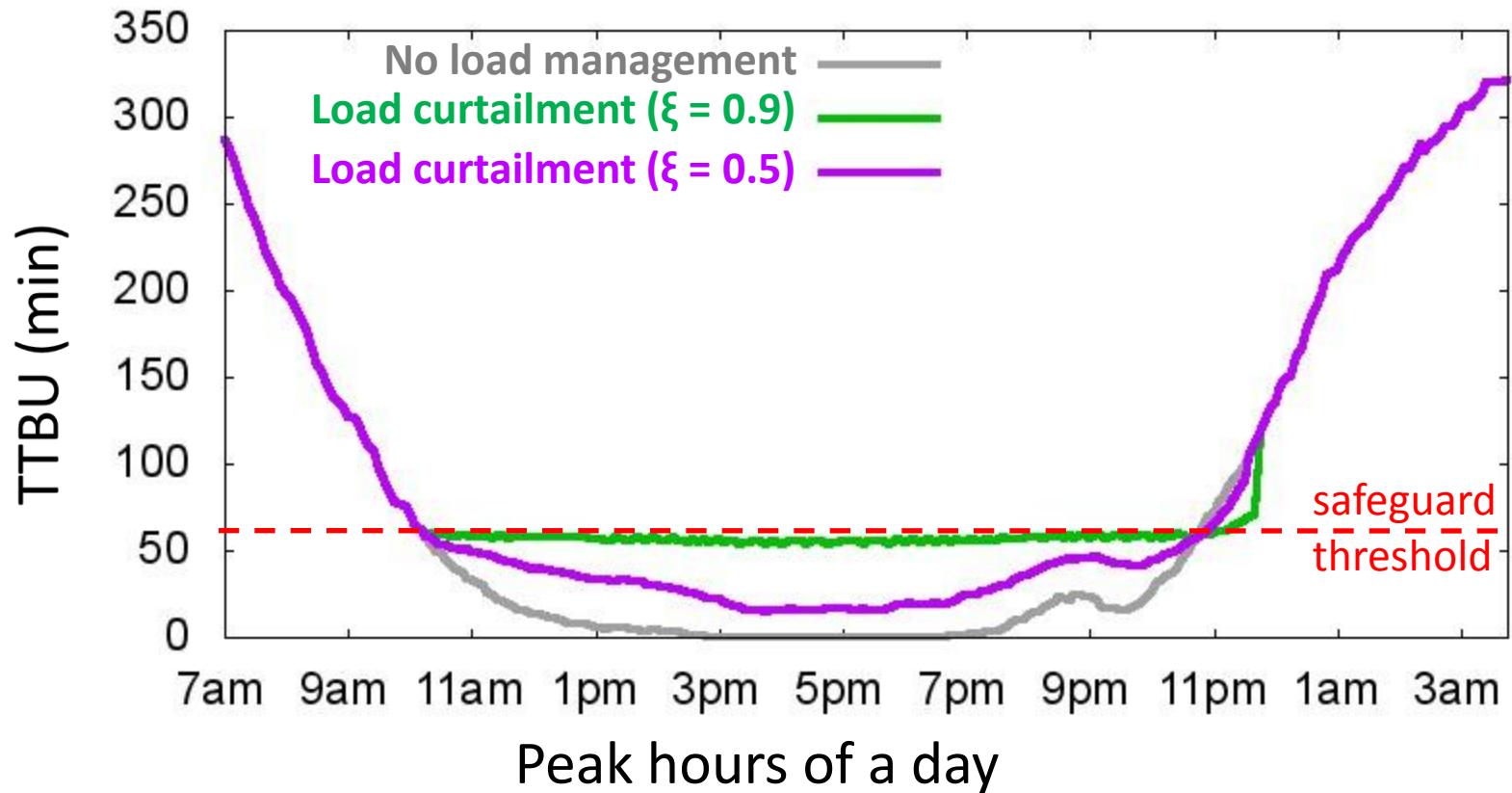
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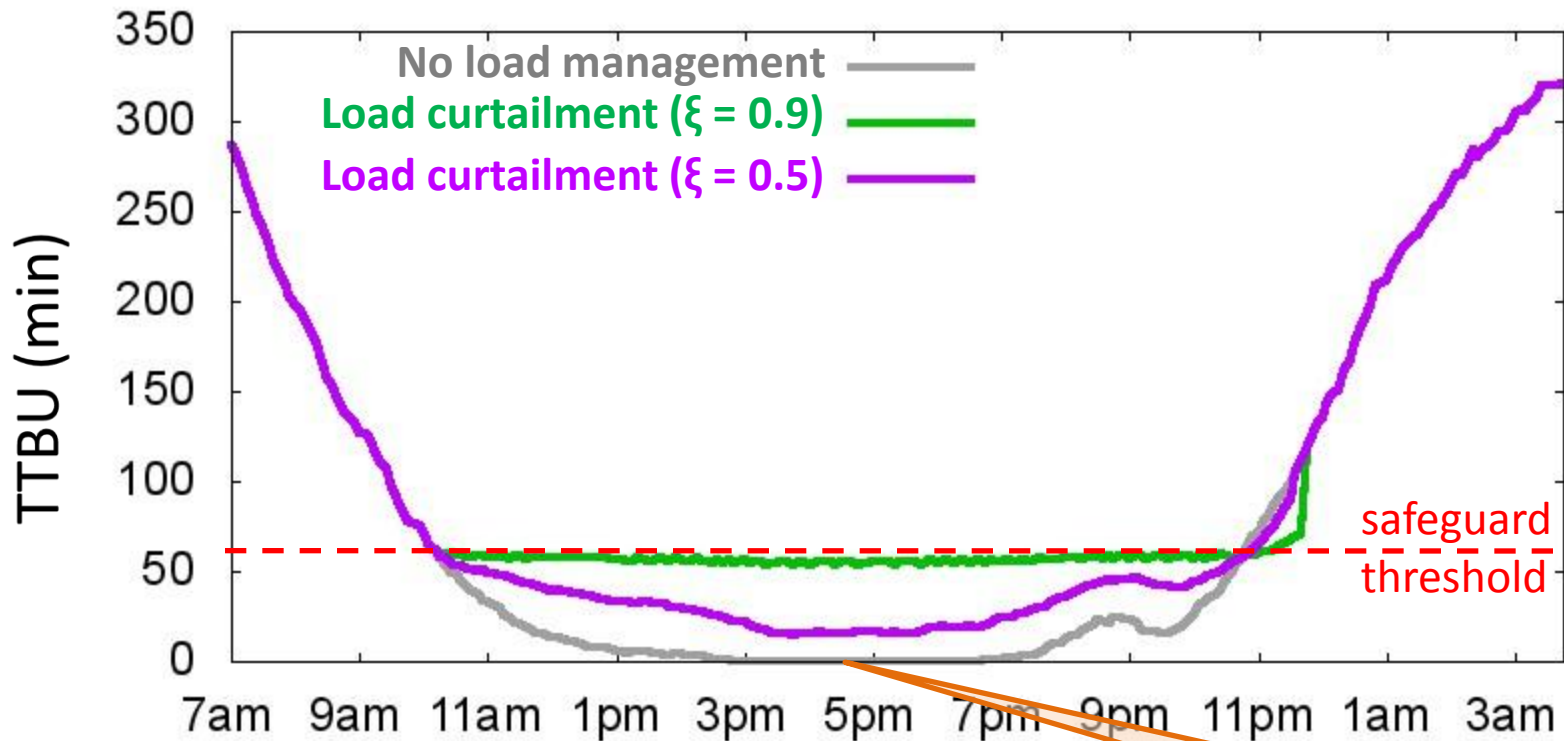
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# Impact of Commitment



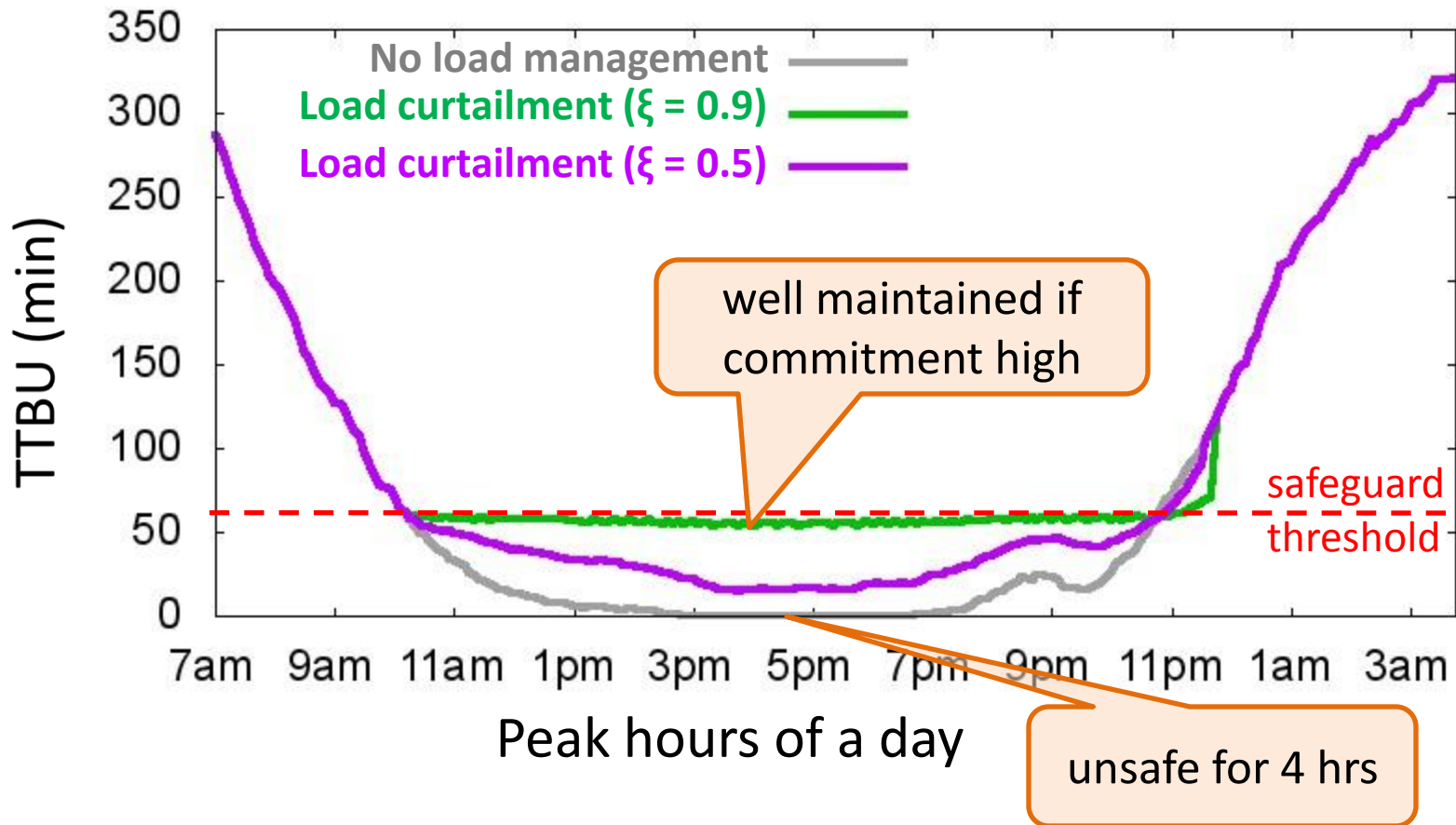
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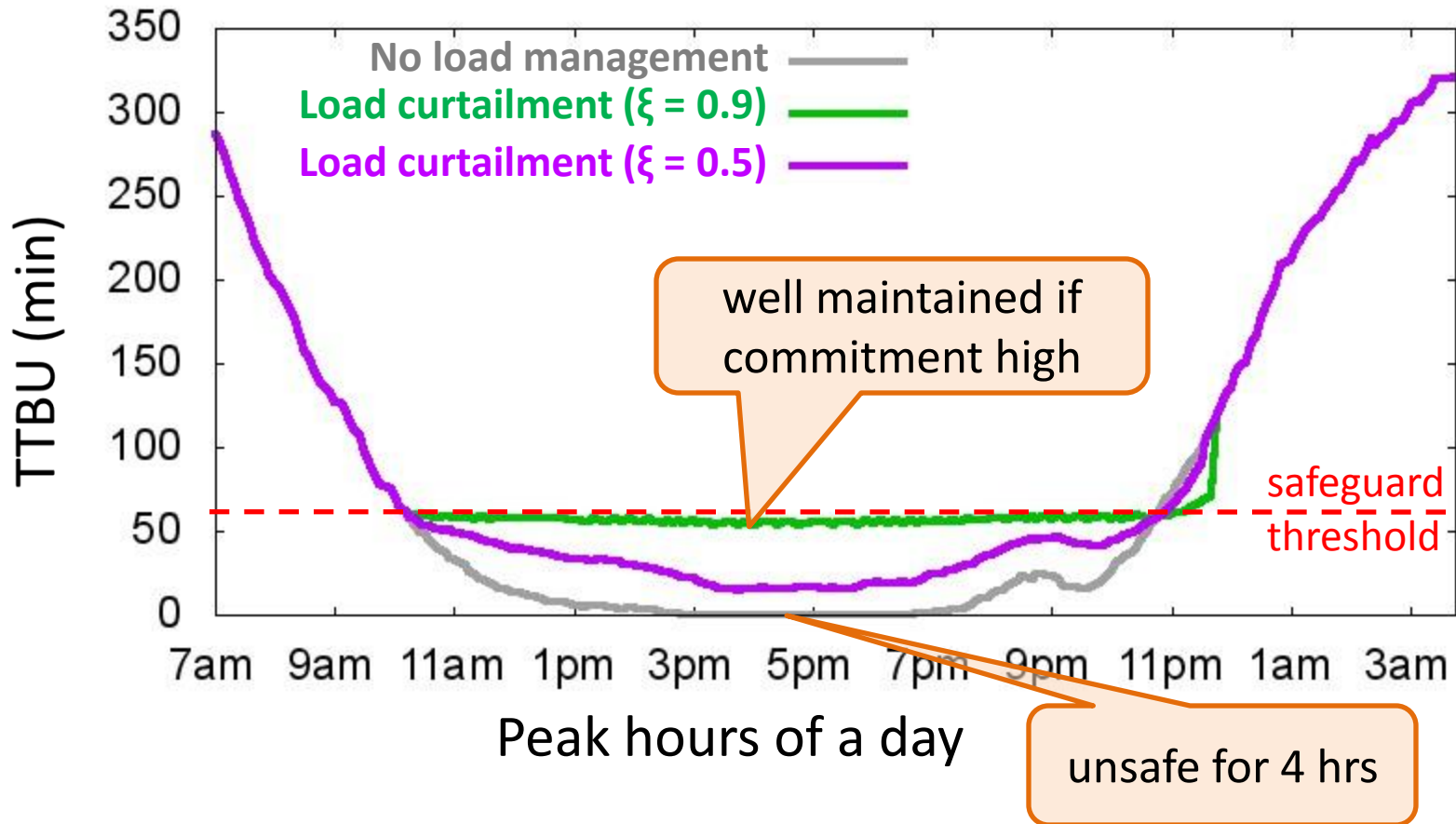
Peak hours of a day

unsafe for 4 hrs

# Impact of Commitment



# Impact of Commitment

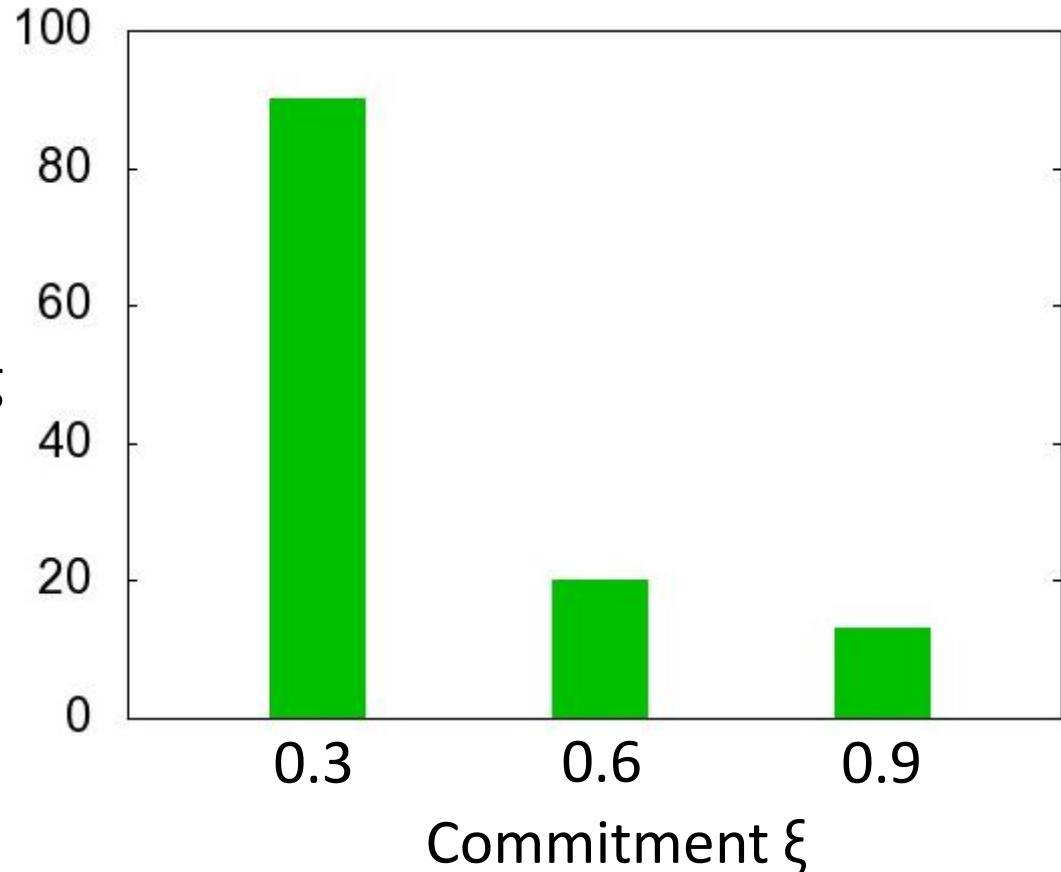


- $\xi > 0.4$ , load shedding avoided



# Setting of Safeguard Threshold

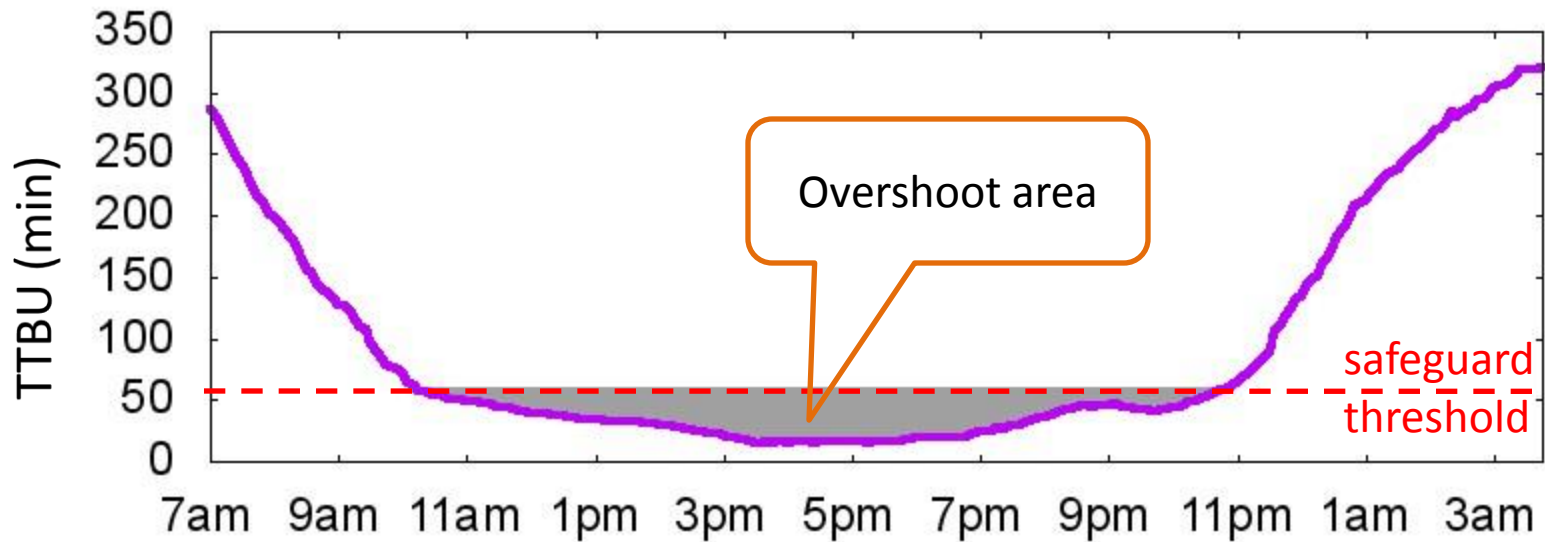
Minimum  
safeguard threshold  
to avoid load shedding  
(minutes)



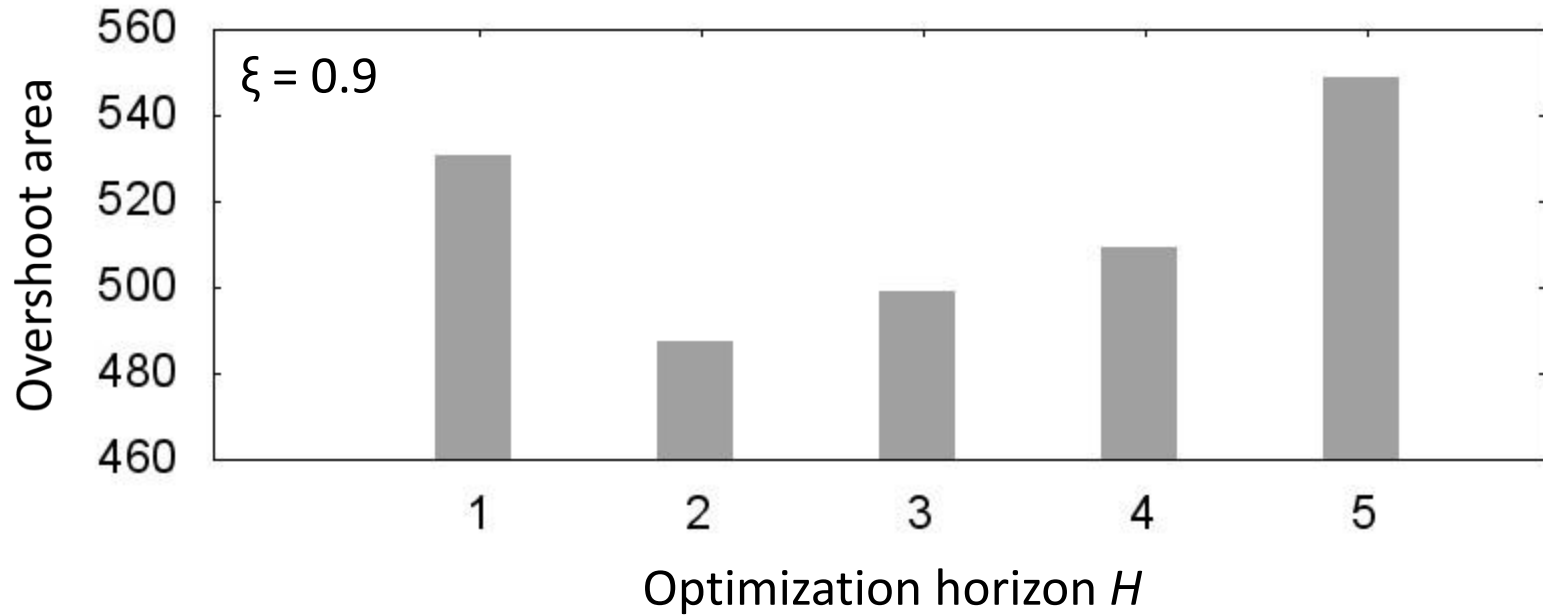
- Low commitment
  - High safeguard

# Impact of Optimization Horizon

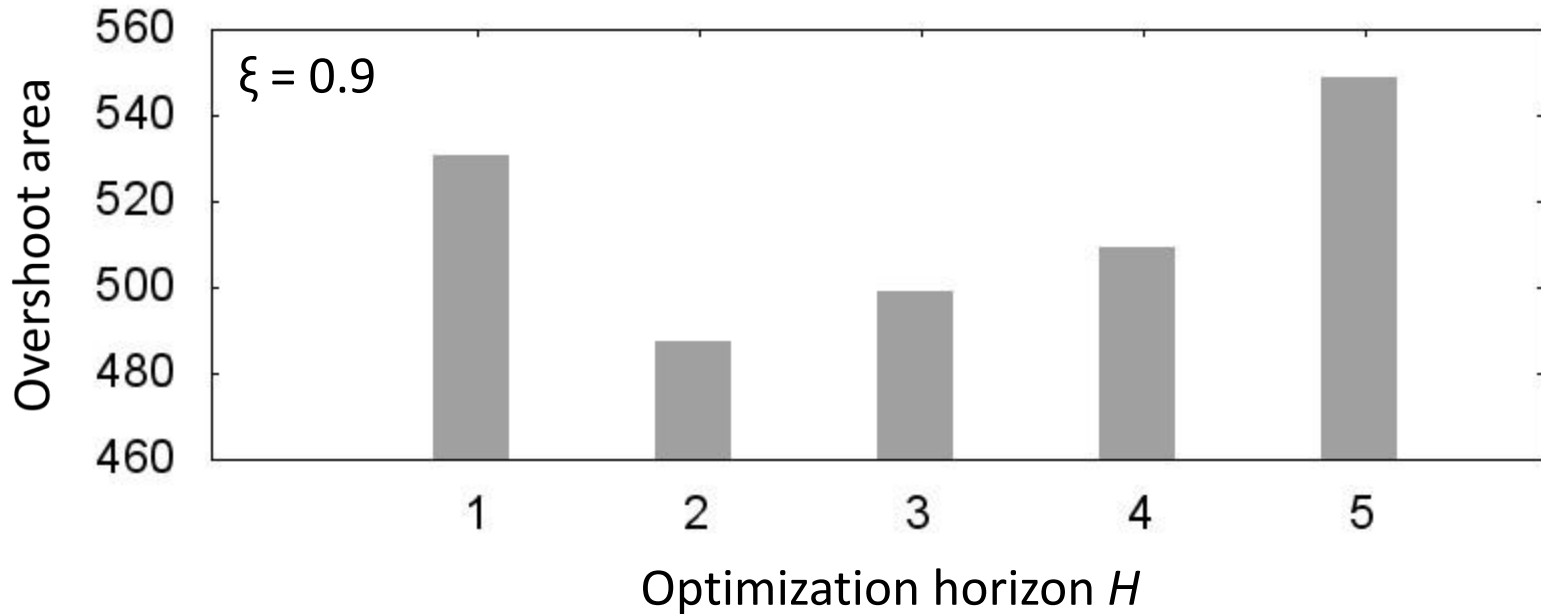
min.  $\sum_{h=1}^H |\text{TTBU}_h - \text{safeguard}|$



# Impact of Optimization Horizon

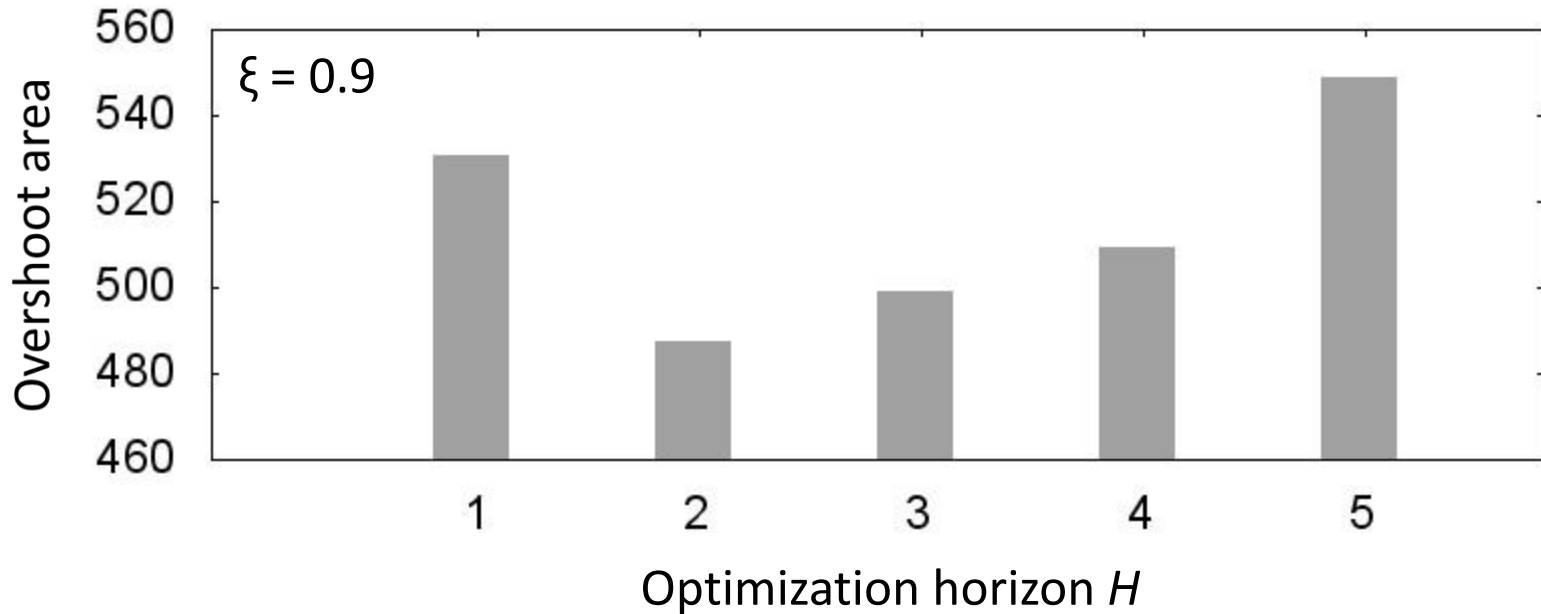


# Impact of Optimization Horizon



- Too small  $H$ 
  - Ignore impact (due to demand inertia) on later steps

# Impact of Optimization Horizon



- Too small  $H$ 
  - Ignore impact (due to demand inertia) on later steps
- Too large  $H$ 
  - Low prediction accuracy

# Conclusion and Future Work

- Safety-assured collaborative load management
  - Time to being unsafe
  - Rapid and predictive safety assessment
  - Predictive curtailment scheduling
- Evaluation on 37-bus system
- Future work
  - Study and integrate empirical commitment models
    - Affected by  $\{x_1, \dots, x_H\}$  and  $\sigma(x_1, \dots, x_H)$