PROBABILISTIC FORECAST OF REAL-TIME LOCATIONAL MARGINAL PRICE

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Overview

- Objectives
  - Investigate the real-time LMP forecast problem by an operator
  - Develop probabilistic forecasting techniques.
  - Incorporate real-time measurements and general load forecast models.
  - Develop scalable computation techniques.
- Summary of results
  - Real-time LMP models for energy only and energy-reserve markets.
  - Forecast methods:
    - A multiparametric linear program (MPLP) approach for ex ante LMP
    - A Markov chain approach for ex ante and ex post LMPs
  - Simulations.

Operator provided real-time LMP forecast

- Benefits
  - Valuable for generation and demand response decisions
  - Risk management
  - Congestion relief and operating cost reduction
  - Examples: ERCOT, AEMO, ….

- Advantages of LMP forecast by an operator
  - Access to real-time data and network operating conditions
  - Access to internal LMP computation state
  - Ability to incorporate load/variable generation forecast models.

The state-of-the-art

- Extensive literature on load forecast
  - Quite accurate and robust performance (1-3%)
  - Both point and probabilistic forecast techniques exist
  - Renewable integration brings new challenges

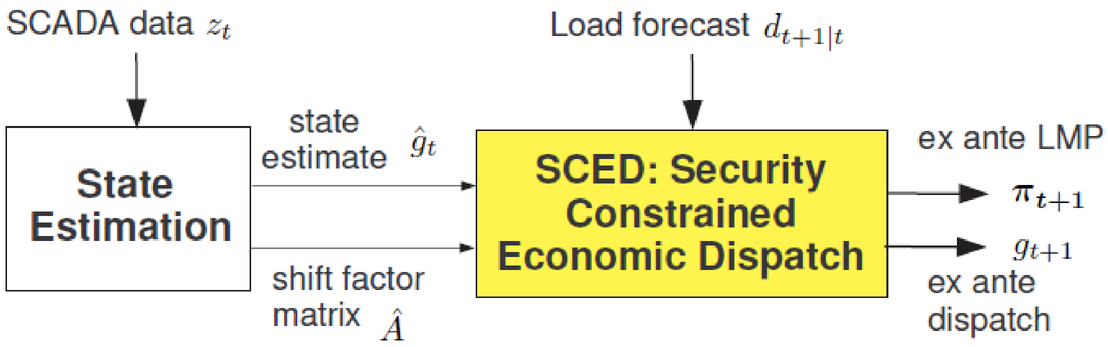
- Considerable literature on day ahead LMP forecast
  - Mostly black box techniques
  - Relatively poor performance (10-20% MAPE)
  - Primarily providing point forecasting
  - Rarely deal with on LMP and network effects

- Very little published work on probabilistic LMP forecast

Outline

- Introduction
- Real-time LMP models (energy & reserve)
  - Ex ante LMP model
  - Ex post LMP model
- Probabilistic Real-time LMP forecast
  - Probabilistic forecast & performance measure
  - A multiparametric linear program (MPLP) approach
  - A Markov chain approach to ex post LMP forecast
- Simulation results

An ex ante real time LMP model



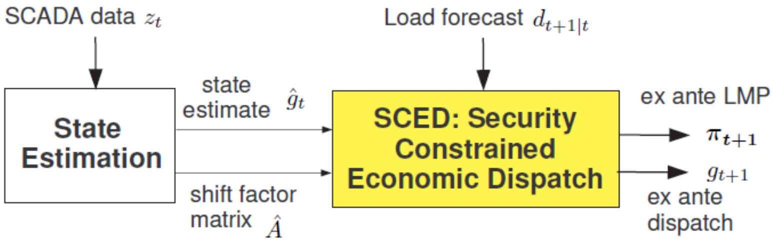
minimize $\quad c^T g$

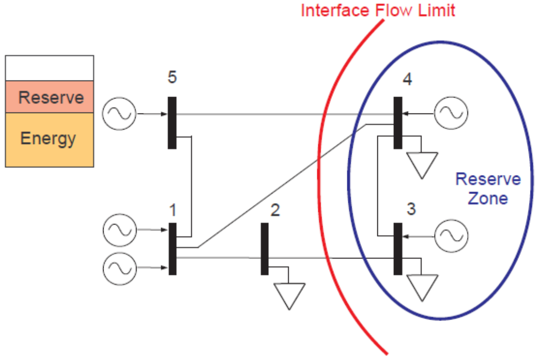
subject to

(λ) :	$\mathbf{1}^T(g - d_{t+1\|t}) = 0,$	power balance,
$(\mu^{+/-})$:	$-F^+ \leq \hat{A}(g - d_{t+1\|t}) \leq F^+,$	transmission constraint,
$(\gamma^{+/-})$:	$g^- \leq g \leq g^+,$	generation capacity,
$(\eta^{+/-})$:	$\hat{g}_t - \Delta^- \leq g \leq \hat{g}_t + \Delta^+,$	ramp limit.

$$\pi_{t+1} = \lambda \mathbf{1} + \hat{A}\mu^+ - \hat{A}\mu^-.$$

An ex ante real time LMP model with co-optimization





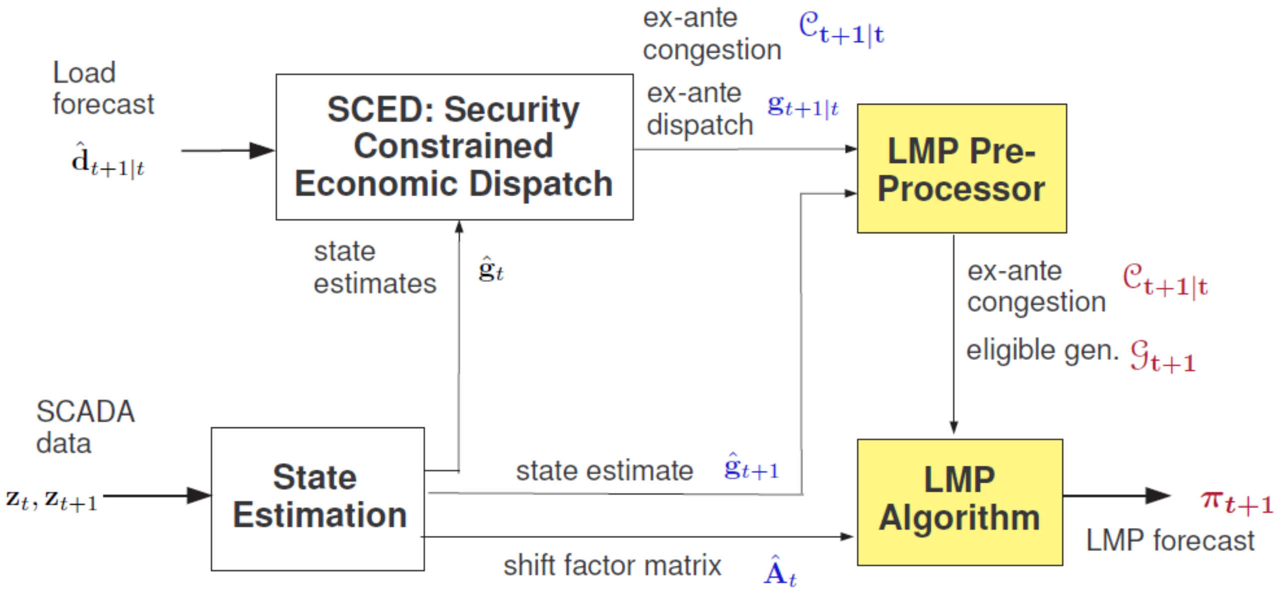
P0: $\min_{g,r,s} c_g^T g + c_r^T r + c_p^T s_l + c_p^T s_s$

subject to:

$$
\begin{array}{lll}
(\lambda): & \mathbf{1}^T(g - d_{t+1|t}) = 0, & \text{energy balance,} \\
(\mu^{+/-}): & -F^+ \leq \hat{A}(g - d_{t+1|t}) \leq F^+, & \text{transmission,} \\
(\alpha): & \delta_{\text{local}}^T r + (I^+ - I) + s_l \geq Q_l, & \text{local reserve,} \\
 & I = \hat{A}_I(g - d_{t+1|t}), & \text{interface flow,} \\
(\beta): & \delta_{\text{system}}^T r + s_s \geq Q_s, & \text{system reserve,} \\
(\gamma^+): & g + r \leq g^+, & \text{generator capacity,} \\
(\nu): & \hat{g}_t - \Delta^- \leq g \leq g_t + \Delta^+, & \text{generation ramp,} \\
(\eta): & 0 \leq r_{i,} \leq r^+, & \text{reserve ramp,} \\
(\gamma^-): & g \geq g^-, & \text{generation capacity,} \\
 & s_l, s_s \geq 0. &
\end{array}
$$

$$\pi_{t+1} = \lambda \mathbf{1} + \hat{A}\mu^+ - \hat{A}\mu^- + \hat{A}_I \alpha$$

An ex post real time LMP model



$$\begin{pmatrix} \mathbf{z}_{t+1} \\ \mathbf{z}_t \\ \hat{\mathbf{d}}_{t+1|t} \end{pmatrix} \xrightarrow{\text{WLS-SE}} \begin{pmatrix} \hat{\mathbf{g}}_{t+1} \\ \hat{\mathbf{g}}_t \\ \hat{\mathbf{d}}_{t+1|t} \end{pmatrix} \xrightarrow{\text{SCED}} \begin{pmatrix} \hat{\mathbf{g}}_{t+1} \\ \mathbf{g}_{t+1|t} \\ \mathcal{C}_{t+1|t} \end{pmatrix} \xrightarrow{\text{LMP Prep}} \begin{pmatrix} \mathcal{G}_{t+1} \\ \mathcal{C}_{t+1|t} \end{pmatrix} \xrightarrow{\text{IDCOPF}} \pi_{t+1}$$

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- Introduction
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  - Ex ante LMP model
  - Ex post LMP model
- Forecast methodology
  - Probabilistic forecast & performance measure
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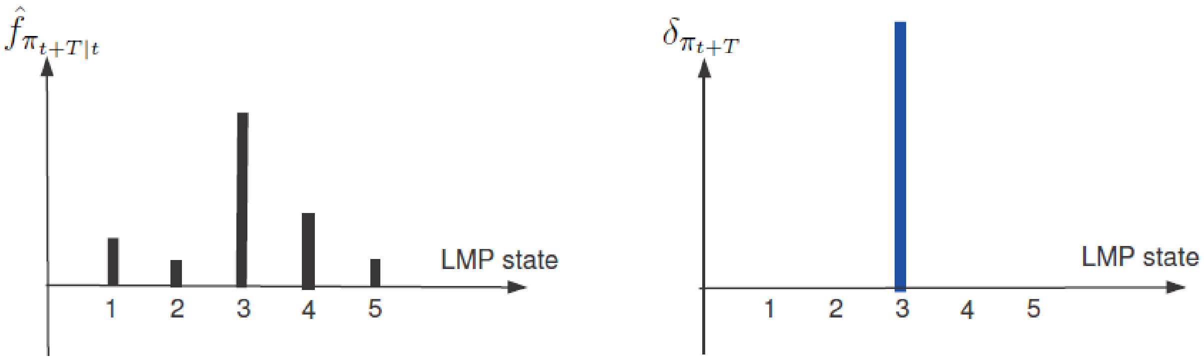
- Simulation results

Point, categorical, and probabilistic forecasts

- ## Point forecast:
  - Predict the specific value of a random variable to be realized in the future
  - Performance measure:
    - mean squared error (MSE), mean absolute error (MAE), and mean percentage error (MAPE).
  - Often leads to parametric approach. Kalman filtering, time series, NN, etc.
- ## Categorical forecast:
  - Predict the (discrete) category of random phenomenon (e.g. prediction interval)
  - Performance measure: Categorical score
  - Very difficult for high dimensional models
- ## Probabilistic forecast:
  - Predict the distribution of a random variable at a future time.
  - Performance measure: (Brier score, KL divergence, total variation…)
  - Very difficult to obtain structured solution in general
  - Bayesian Monte Carlo techniques + problem specific properties.

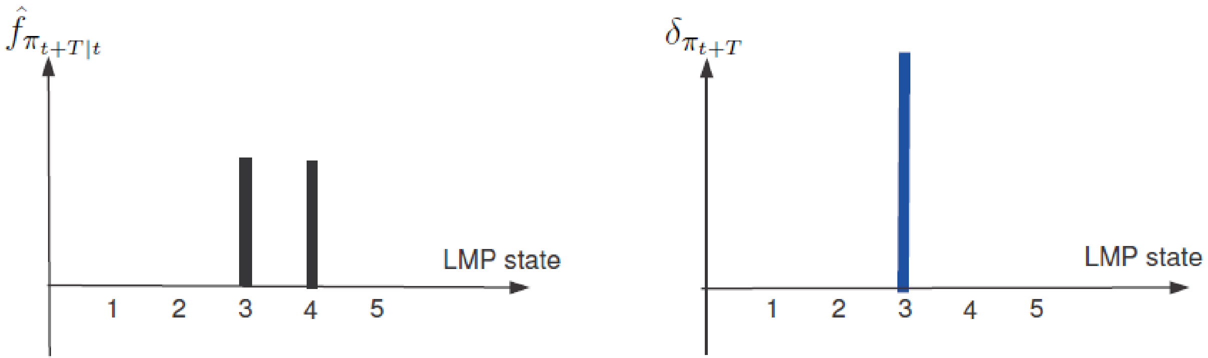
Distribution forecast



- The Brier score is defined by

$$\mathcal{B}(\hat{f}) = \mathbb{E}\left(||\hat{f}_{\pi_{t+T|t}} - \delta_{\pi_{t+T}}||^2 \right)$$

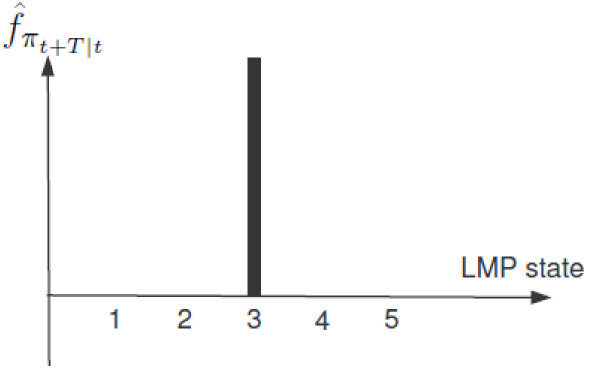
Categorical forecast

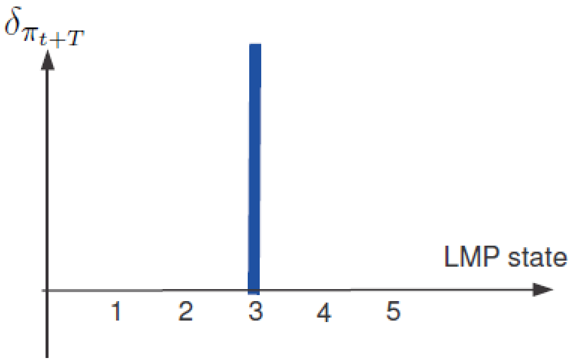


- The performance of a categorical forecast is measured by the tradeoff between sharpness and the accuracy of the forecaster.
- The categorical score of $\hat{P}_{t+T|t}$ is defined by

$$\mathcal{C}(\hat{P}_{t+T|t}) \triangleq \frac{|\hat{\mathcal{P}}_{t+T|t}|}{|\Omega|} + \Pr\left[\pi_{t+T} \notin \hat{\mathcal{P}}_{t+T|t}\right]\left(1 - \frac{|\hat{\mathcal{P}}_{t+T|t}|}{|\Omega|}\right)$$

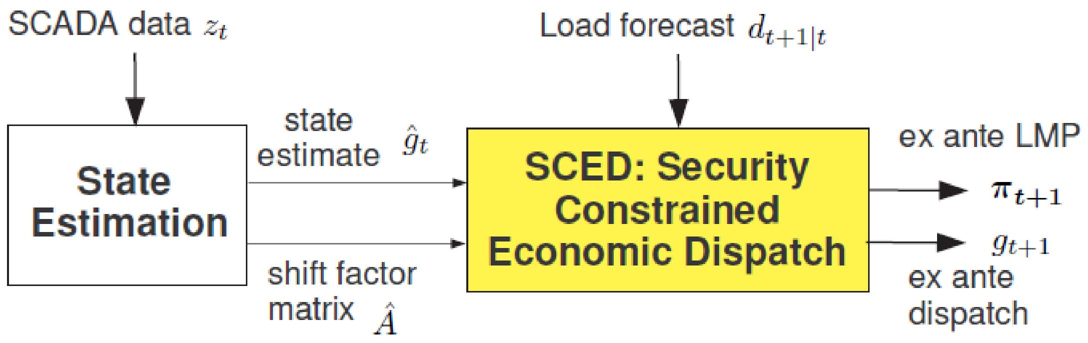
Point forecast



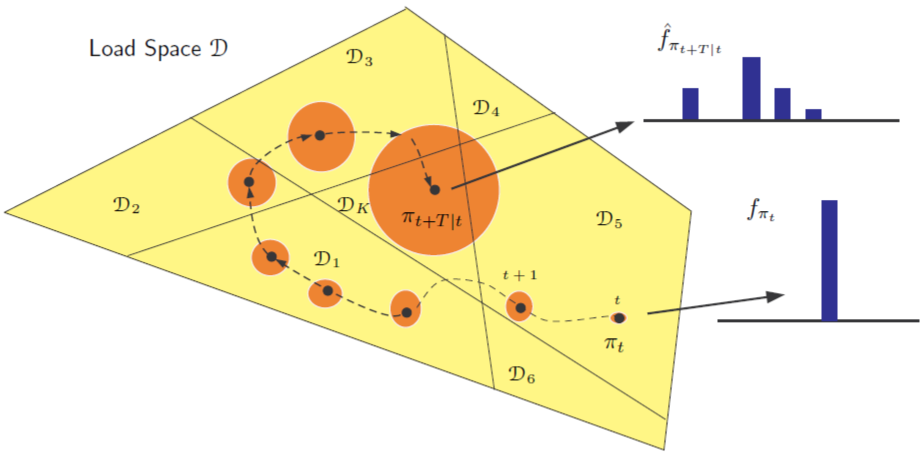


- Point forecaster is a categorical forecaster of size 1.
- The performance of a point forecaster can be measured by
  - probability of error: $\mathcal{E}_p = \Pr(\hat{\pi}_{t+T|t} \neq \pi_{t+T})$.
  - mean squared error (MSE): $\mathcal{E}_{\mathsf{MSE}} = \mathbb{E}(||\hat{\pi}_{t+T|t} - \pi_{t+T}||_2^2)$.
  - mean absolute error (MAE): $\mathcal{E}_{\mathsf{MAE}} = \mathbb{E}(||\hat{\pi}_{t+T|t} - \pi_{t+T}||_1)$.
  - mean absolute percentage error (MAPE): $\mathcal{E}_{\mathsf{MAPE}} = \frac{\mathbb{E}(||\hat{\pi}_{t+T|t} - \pi_{t+T}||_1)}{\mathbb{E}(||\pi_{t+T}||_1)}$.

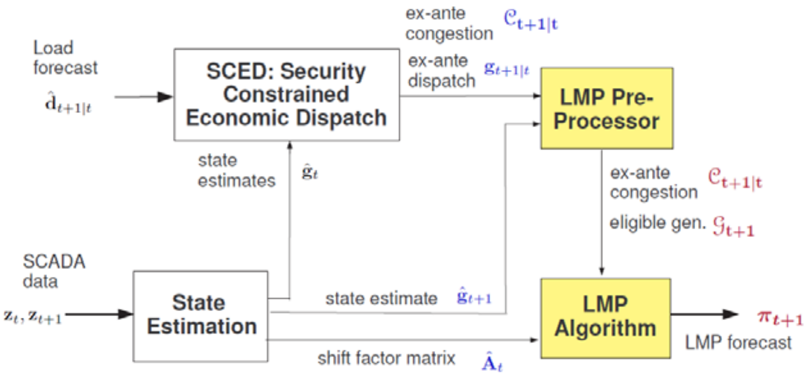
MPLP forecast

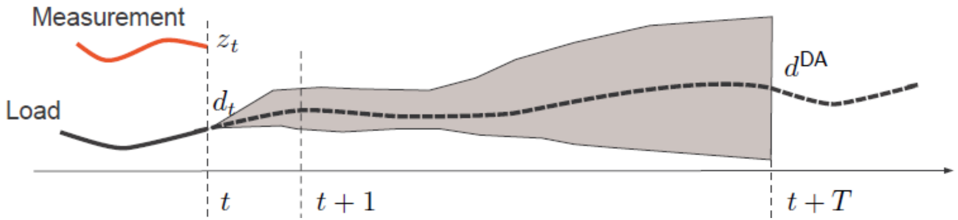


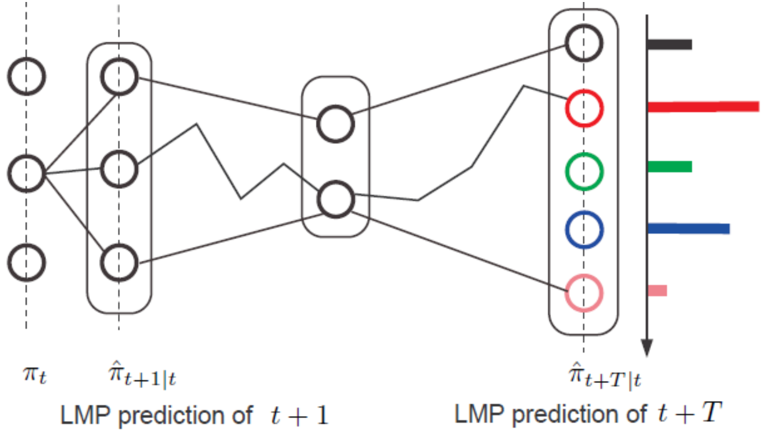
$$
\begin{aligned}
&\text{minimize} \quad c^T g \\
&\text{subject to} \\
&(\lambda): \quad \mathbf{1}^T(g - d_{t+1}) = 0, \\
&(\mu^{+/-}): \quad -F^+ \le \hat{A}(g - d_{t+1}) \le F^+, \\
&(\gamma^{+/-}): \quad g^- \le g \le g^+, \\
&(\eta^{+/-}): \quad Bd_t - \Delta^- \le g \le Bd_t + \Delta^+, \\
&\qquad \pi_{t+1} = \lambda \mathbf{1} + \hat{A}\mu^+ - \hat{A}\mu^-.
\end{aligned}
$$



Forecast of ex post LMP via Markov chain







$$\begin{pmatrix} \mathcal{G}_{t+1} \\ \mathcal{C}_{t+1|t} \end{pmatrix} \xrightarrow{\text{LMPA}} \pi_{t+1} = \begin{bmatrix} \pi_{t+1}^{(1)} \\ \vdots \\ \pi_{t+1}^{(n)} \end{bmatrix}$$

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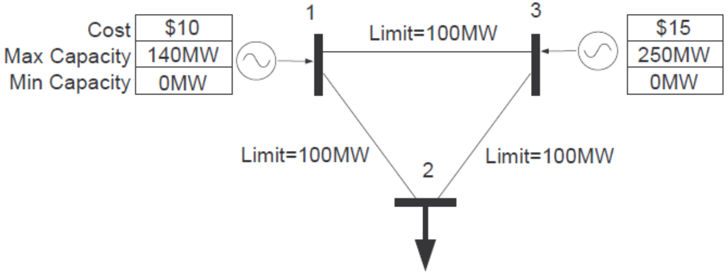
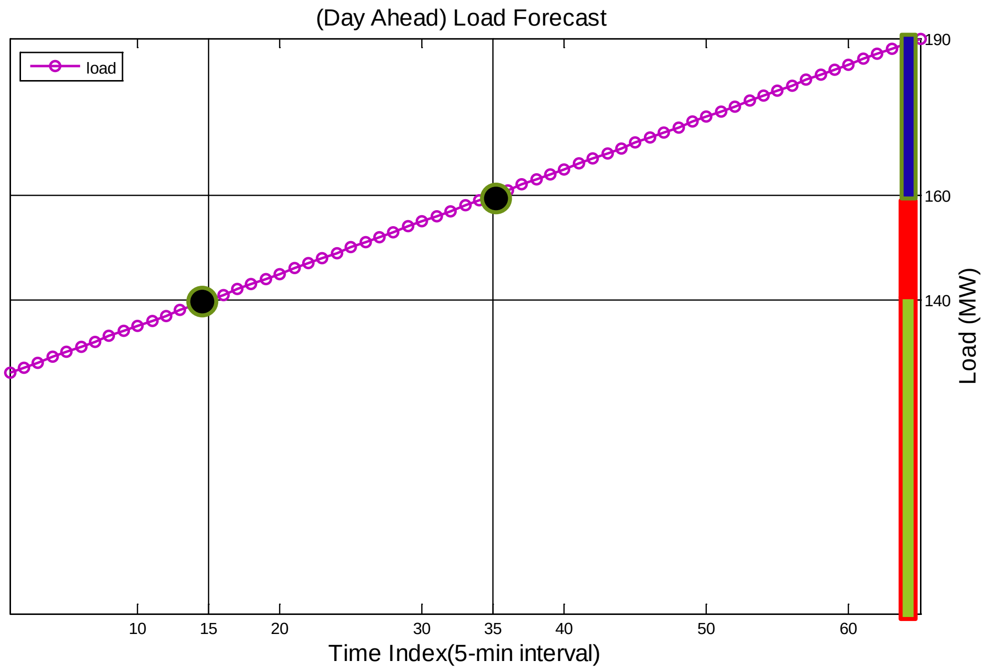
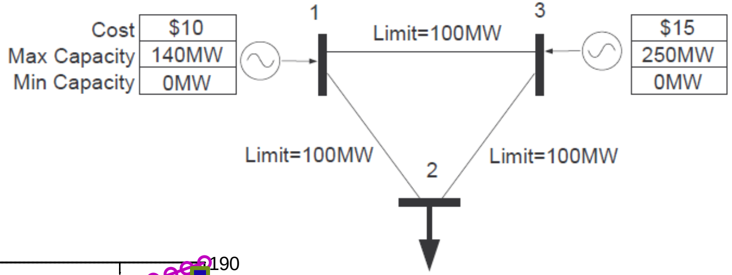
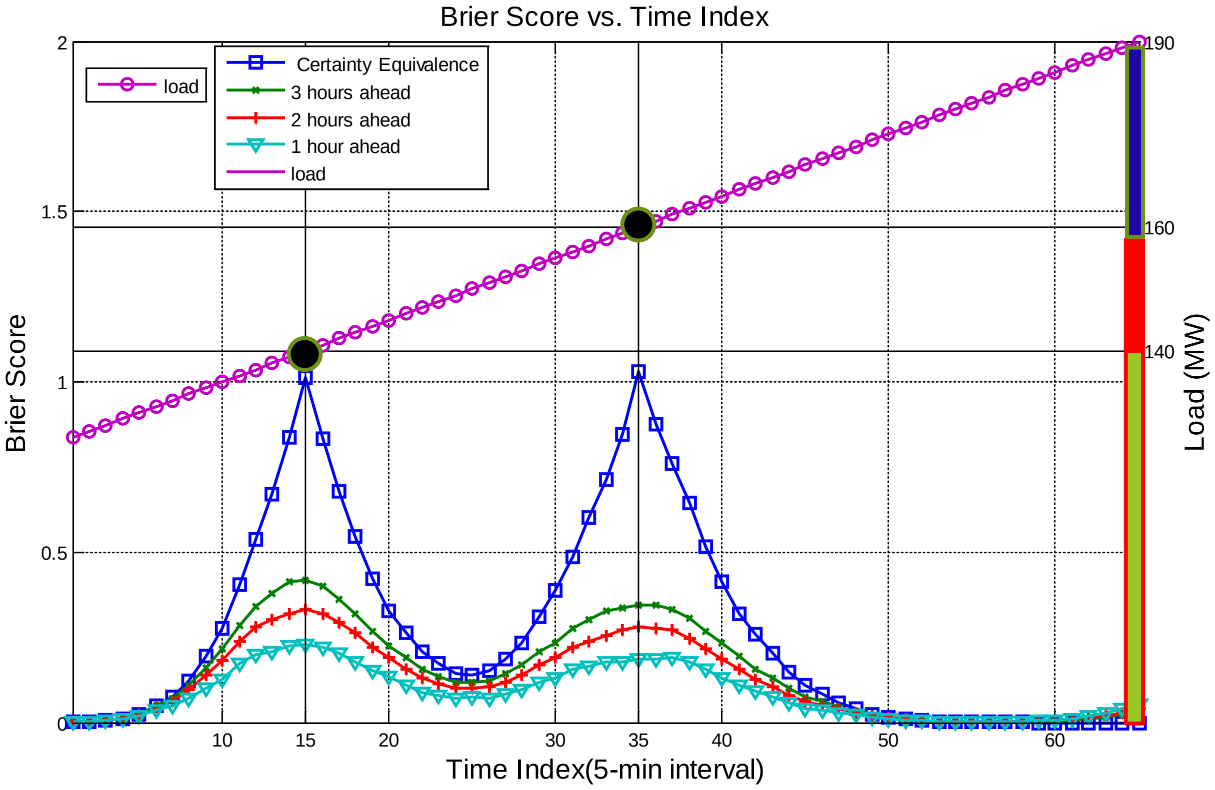
1D (mean) load trajectory



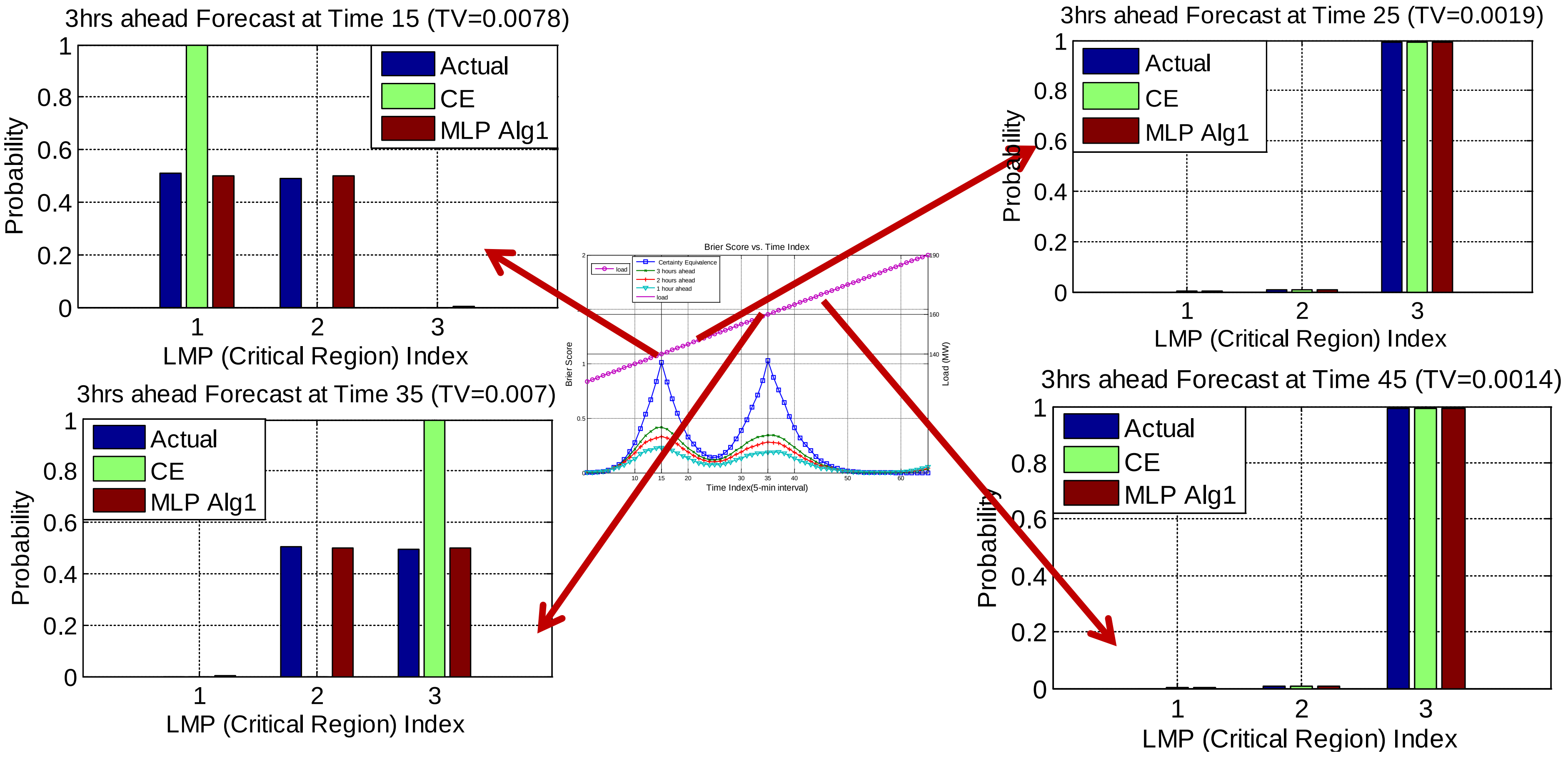


LMP forecast with 1D load

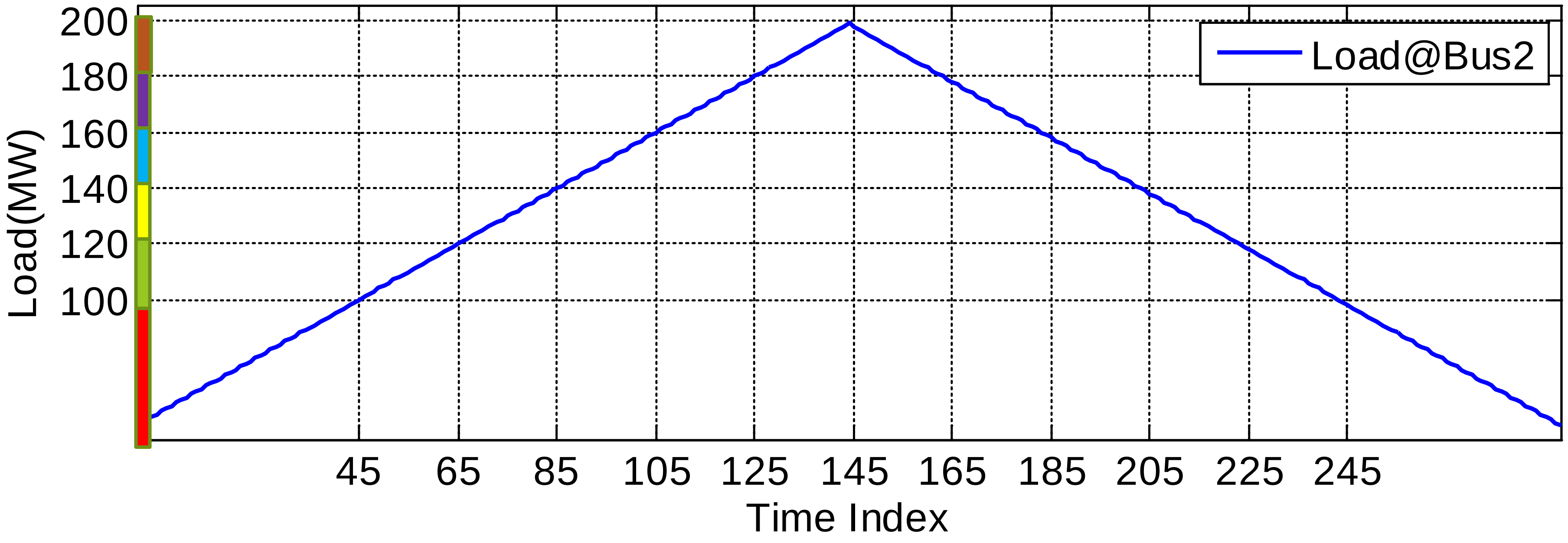




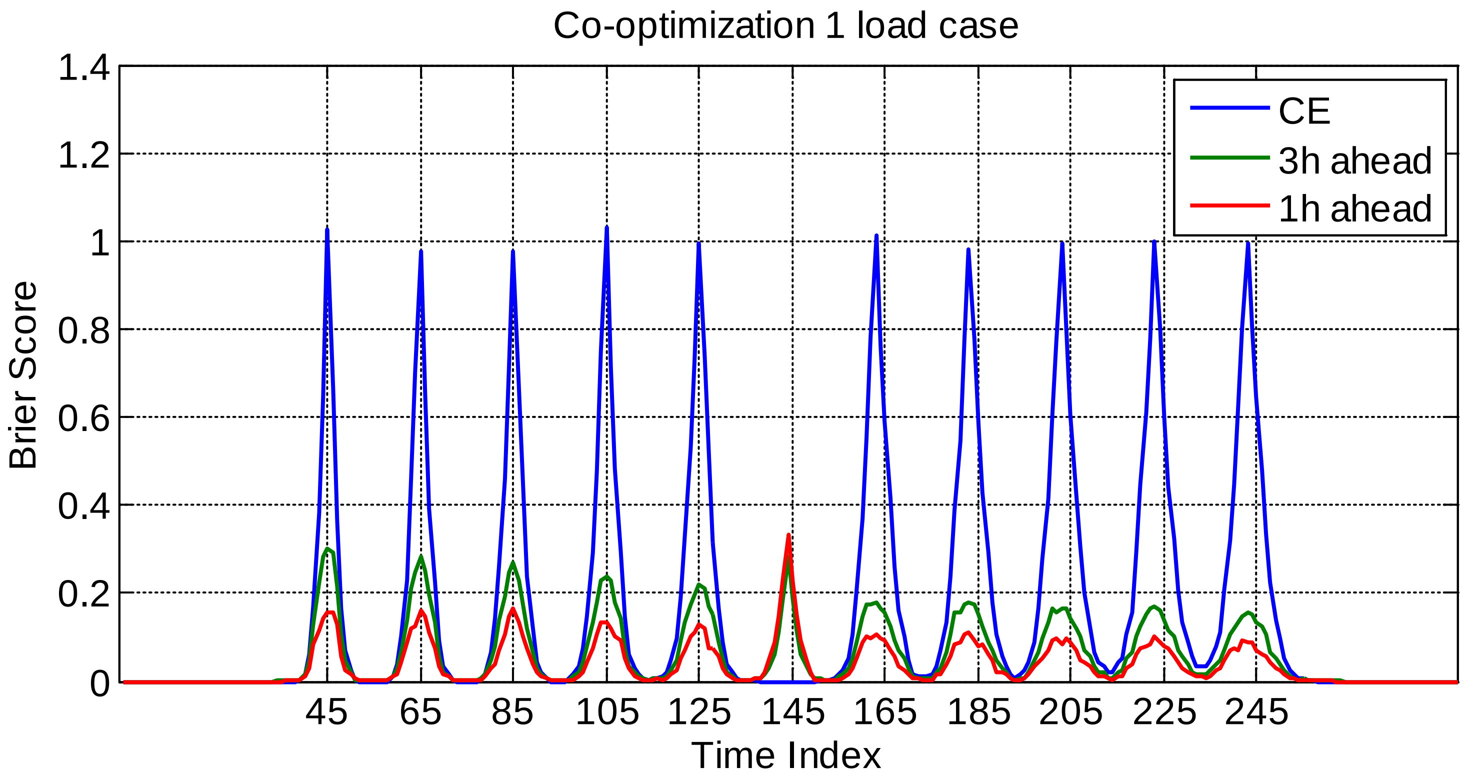
LMP forecast with 1D load



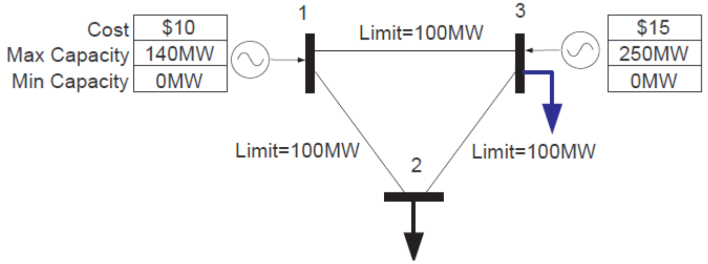
LMP forecast with energy-reserve co-optimization

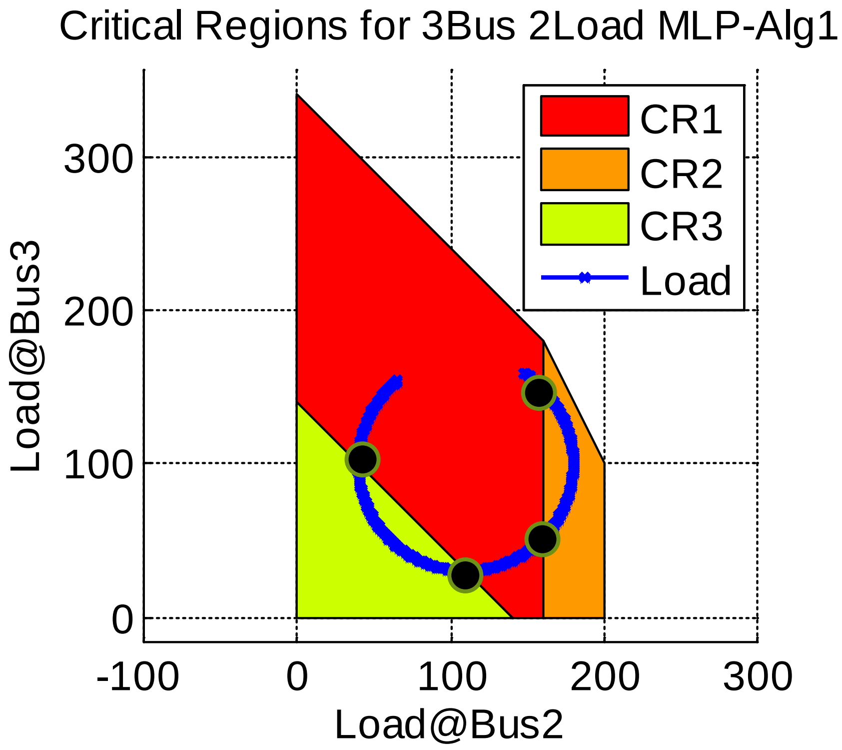


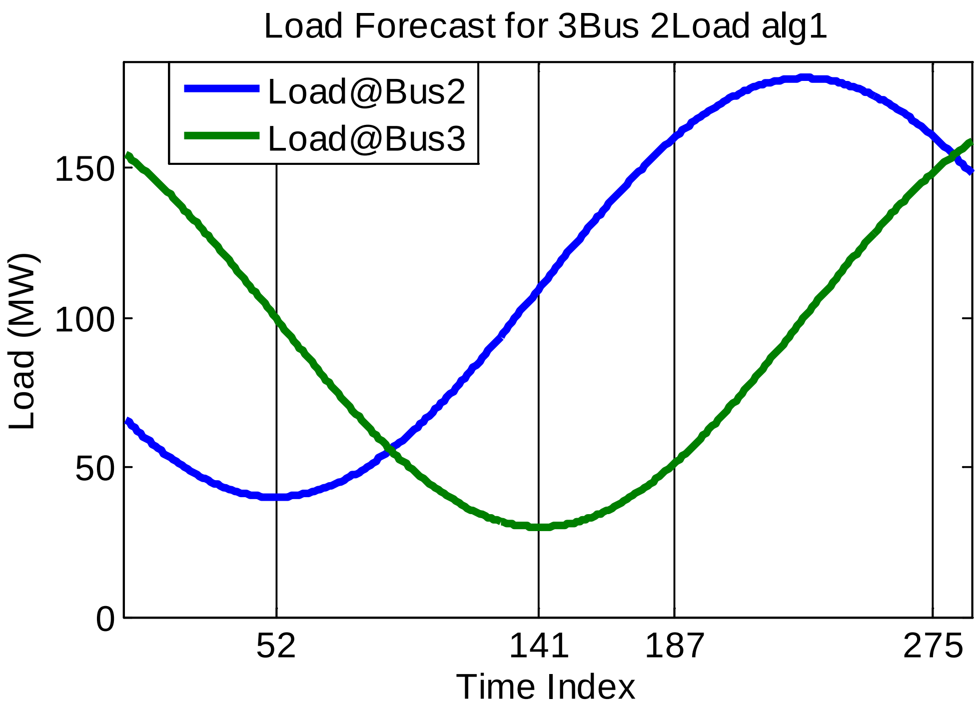
LMP forecast with energy-reserve co-optimization



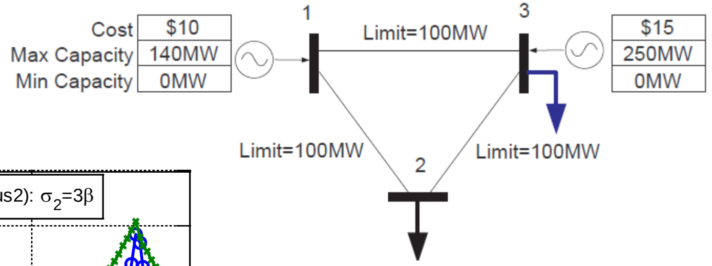
2D (mean) load trajectory

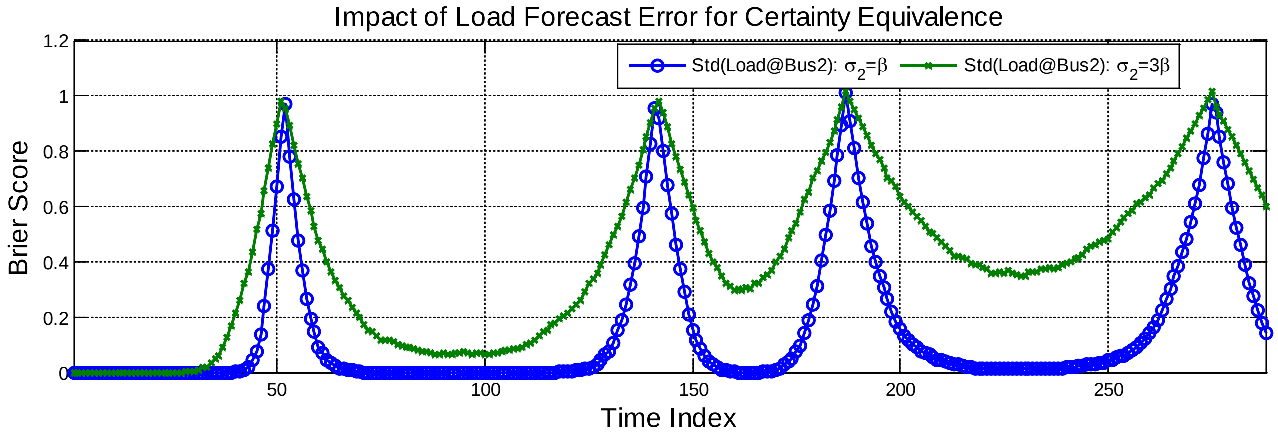


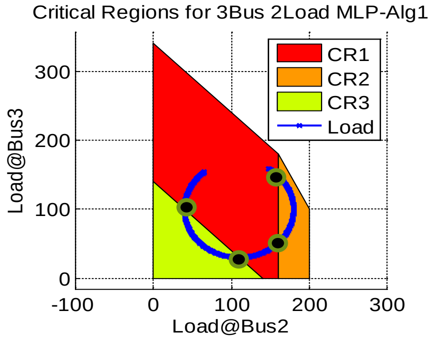


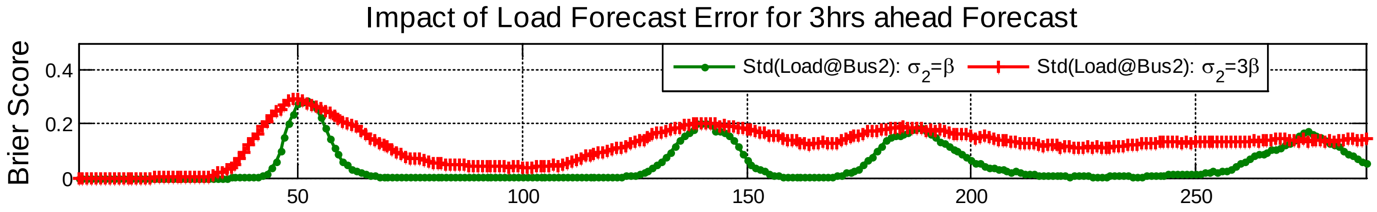


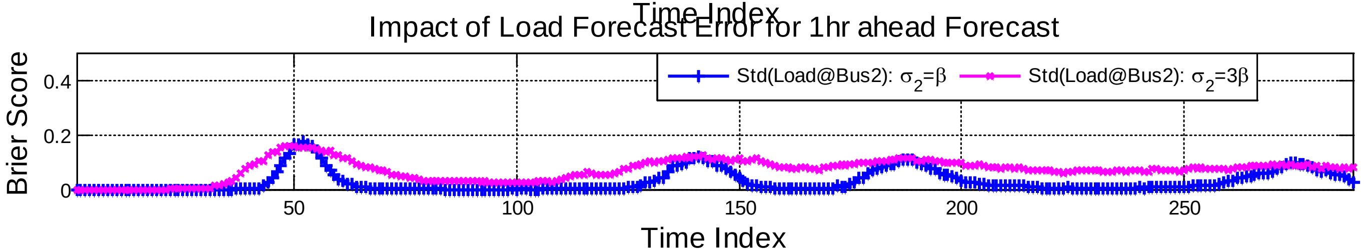
Load uncertainties



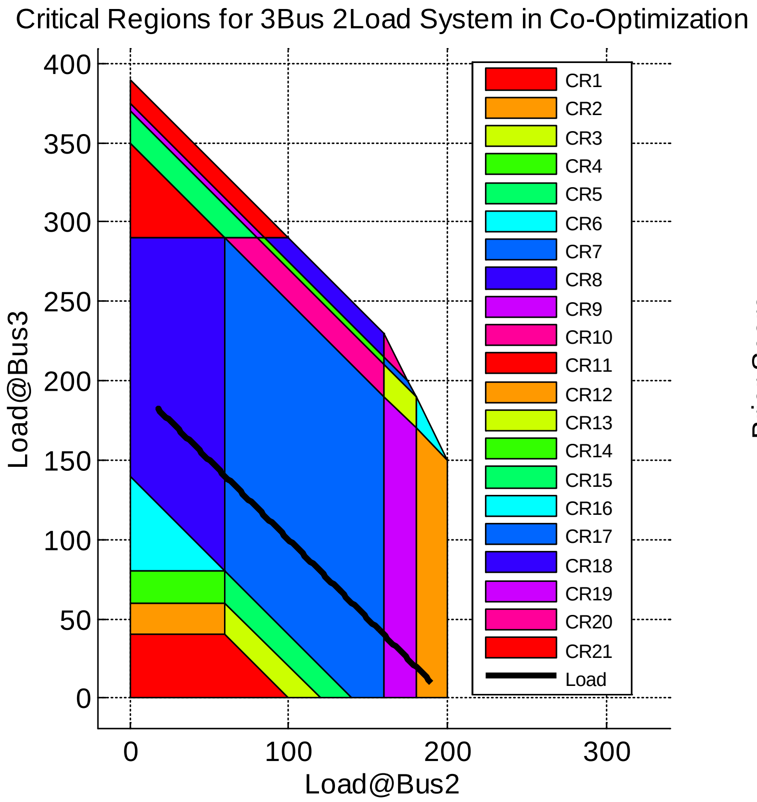


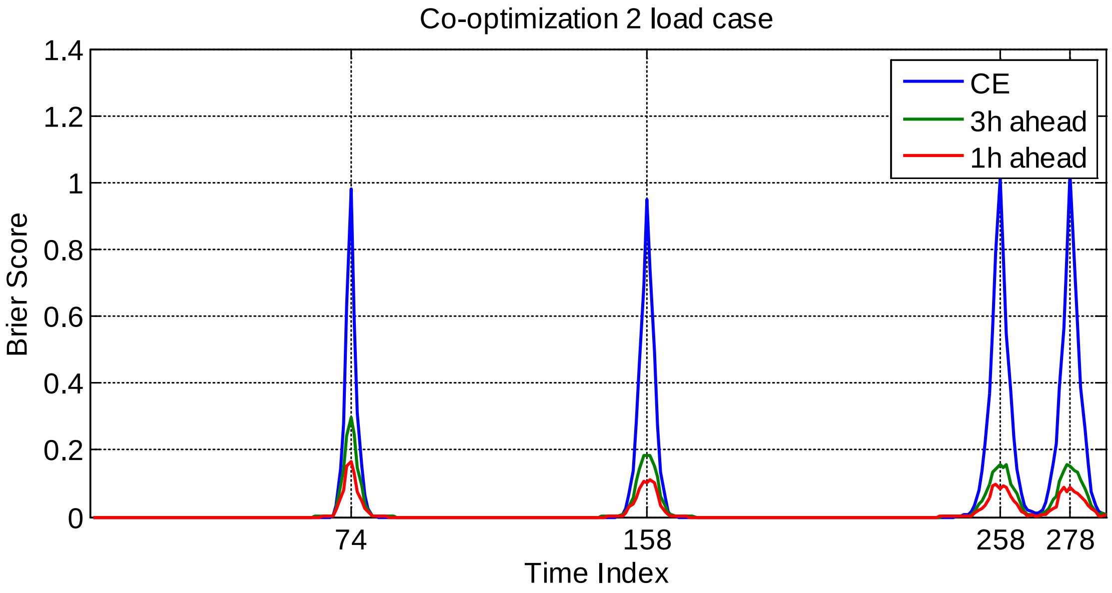




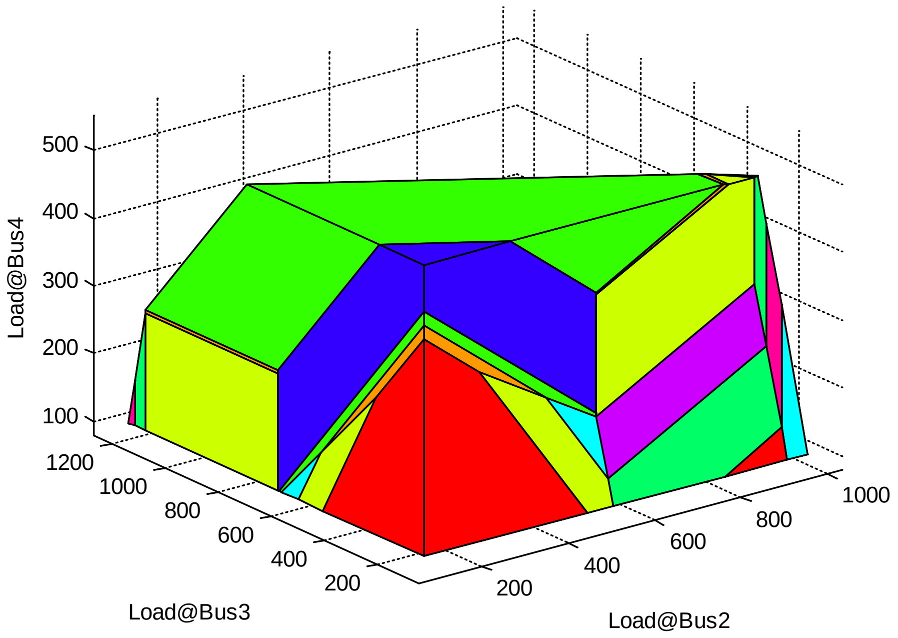


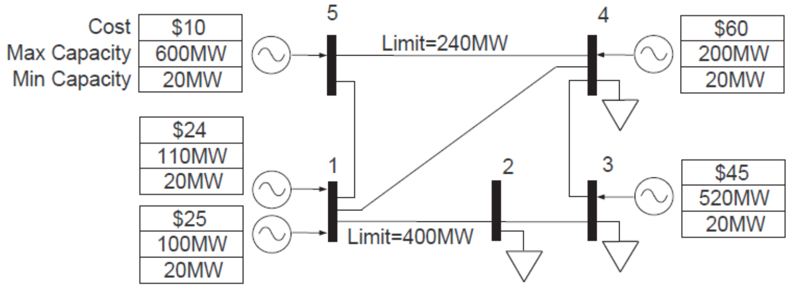
3 bus 2D system with energy-reserve co-optimization

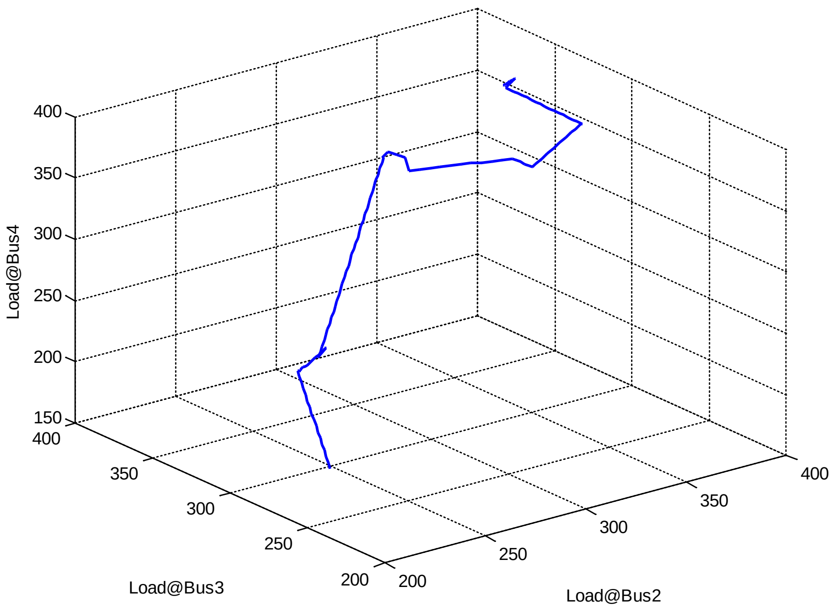




5 bus 3D load system







Sample paths of ex post LMP

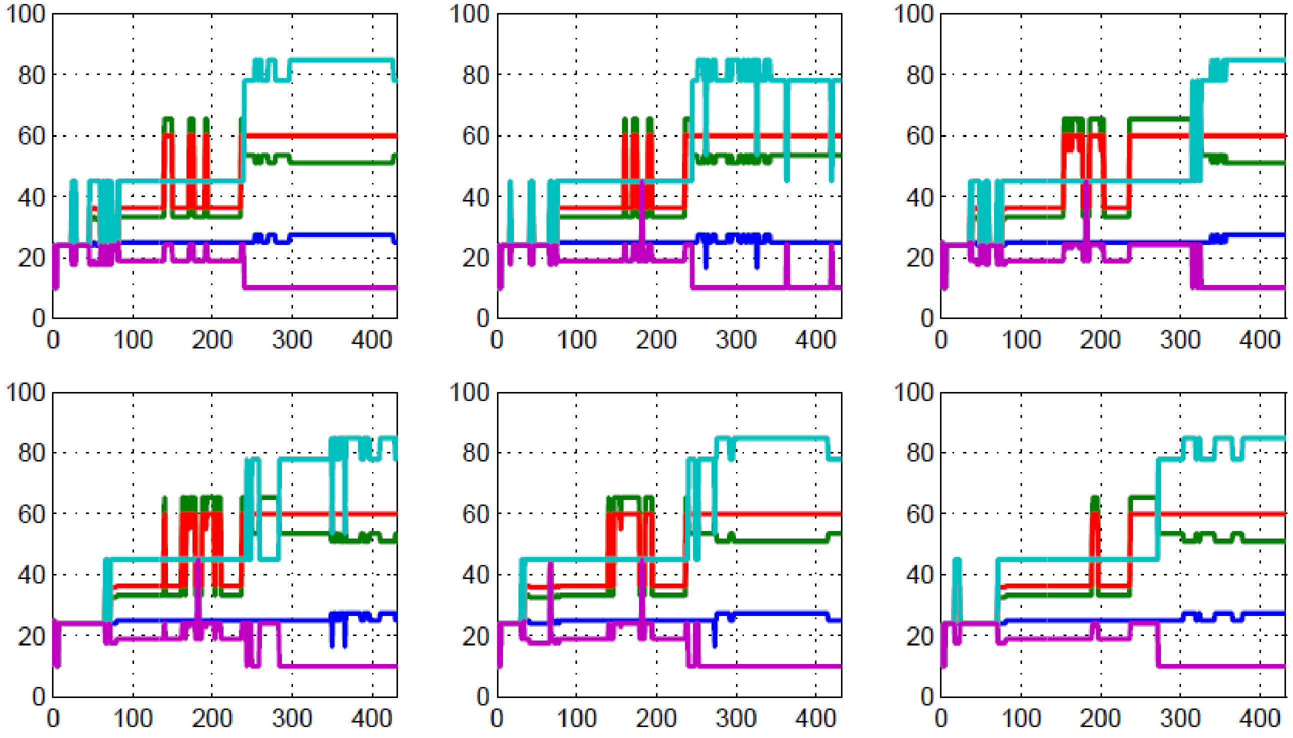
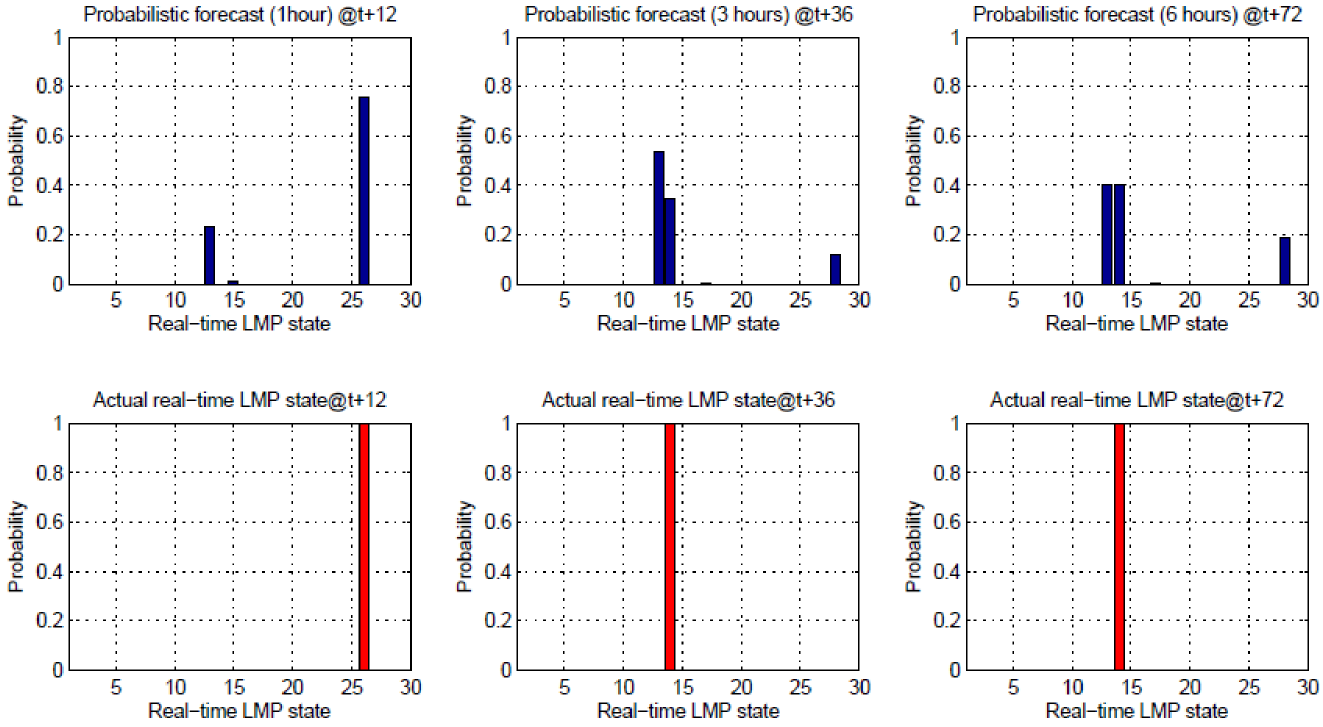
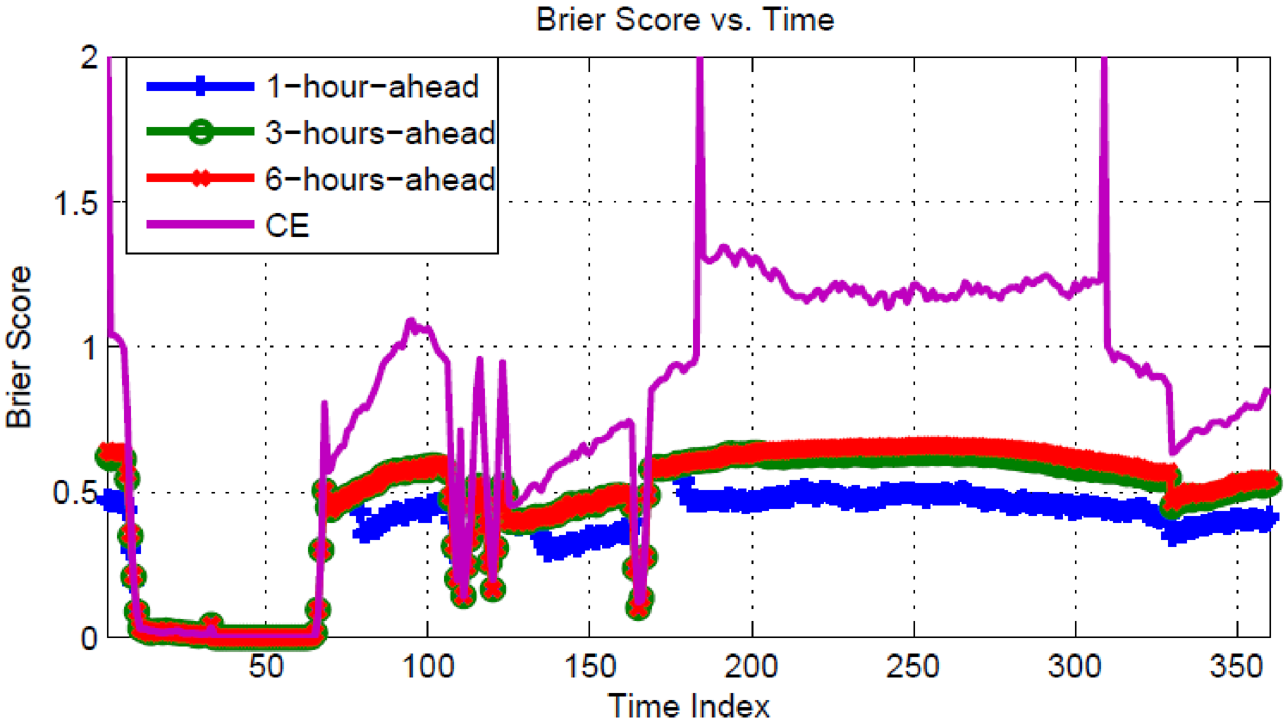


Figure : Real-Time LMP ($/MW) vs. Time Index

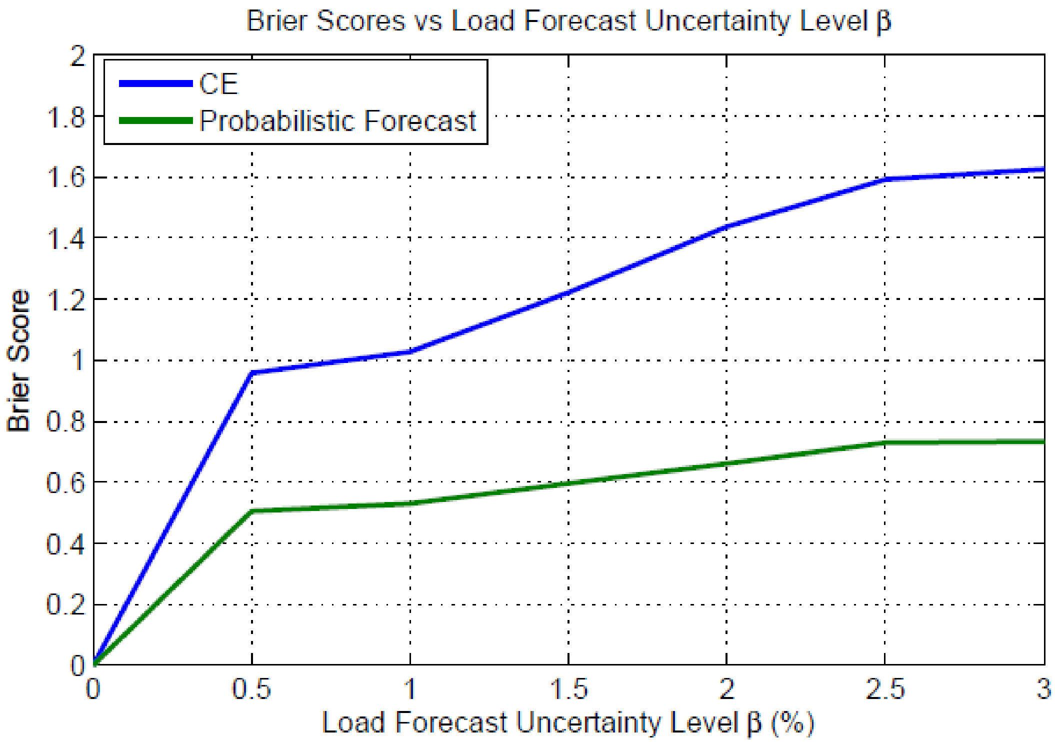
Sample forecasts



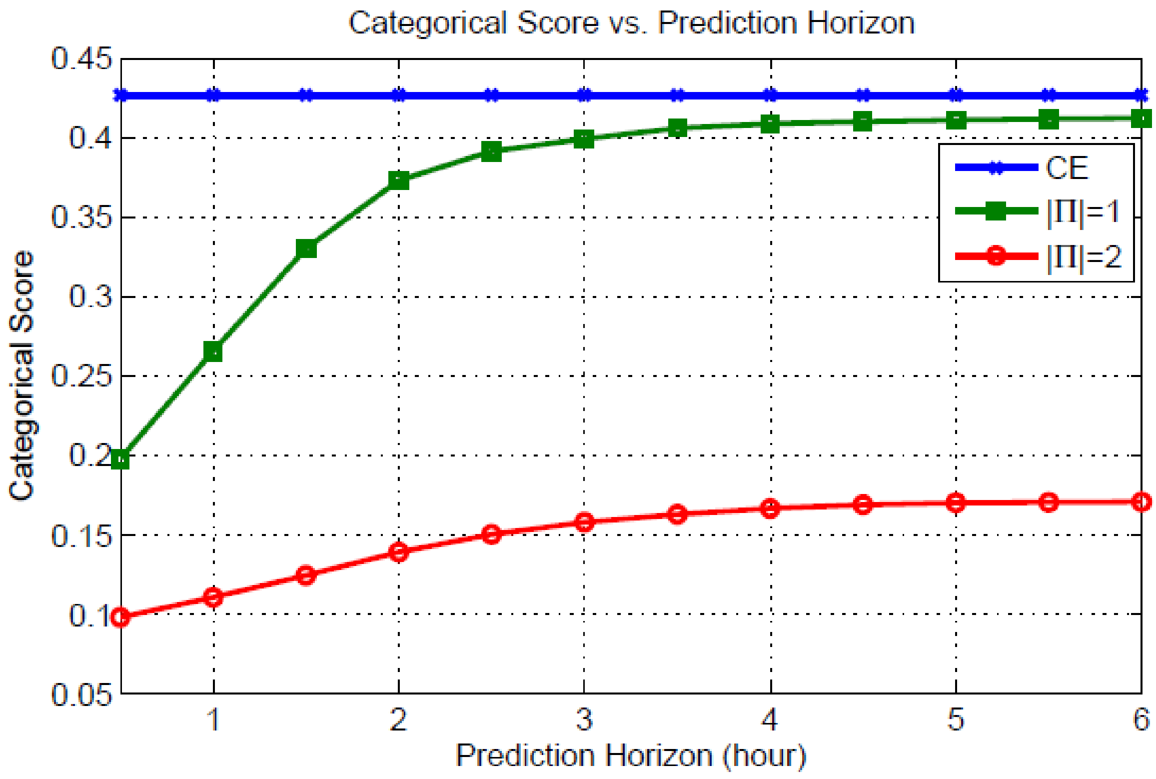
Performance of Markov distribution forecast



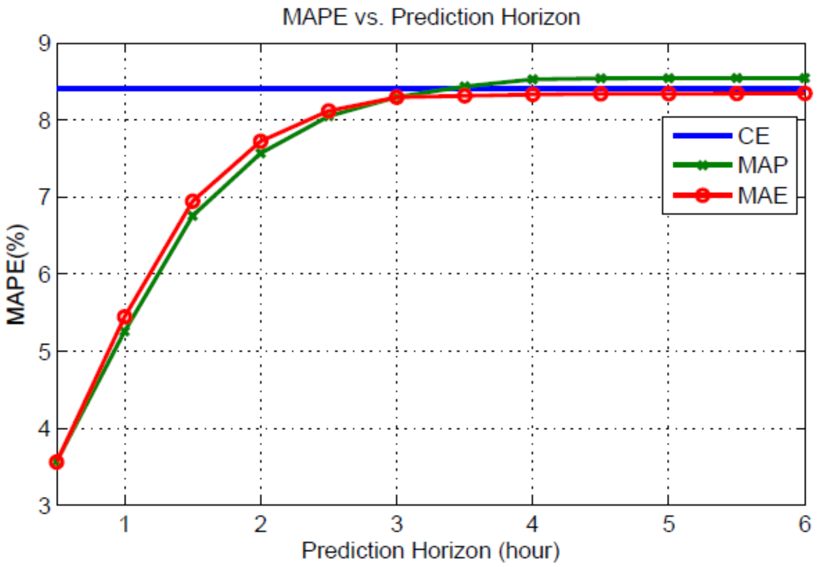
Effects of load uncertainty

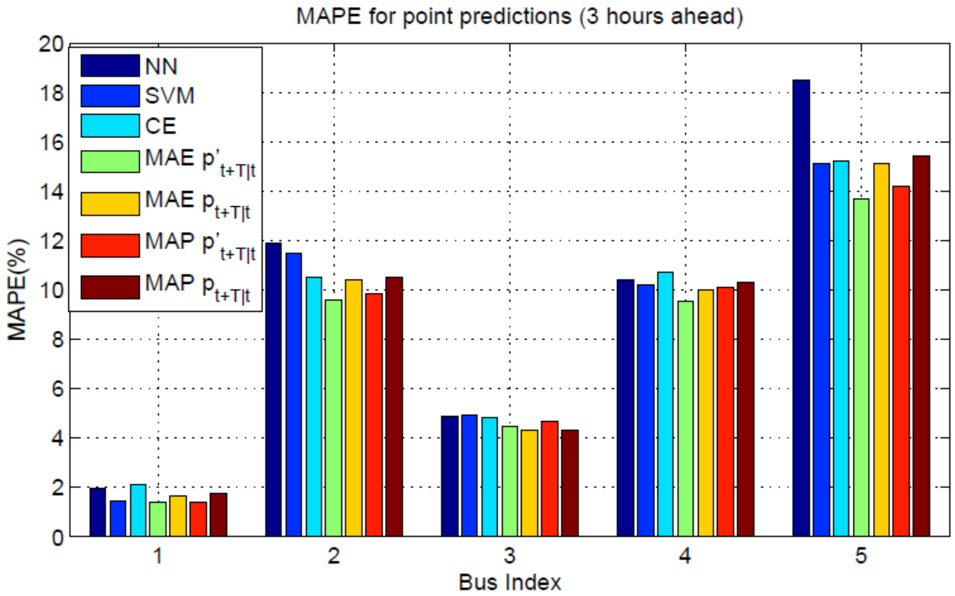


Categorical score of MAP and "best of two"



MAPE performance





Summary and future work

- Summary of results
  - Real-time LMP process is highly structured
  - Real-time LMP models that incorporating forecasting and measurement uncertainties and real-time measurements (e.g. SCADA/PMU).
  - Probabilistic forecast techniques
    - A multi-parametric linear program approach for ex ante LMP forecast
    - A Markov chain approach for ex post LMP forecast
- Future work
  - LMP forecast with renewable generation
  - Toward a scalable solution
    - Approximate MPLP
    - Efficient Monte Carlo techniques