Goals and Challenges in Developing Extended Locational Marginal Pricing

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The work described in this presentation was performed while the author was employed by the Midwest Independent Transmission System Operator (MISO) since renamed the Midcontinent Independent System Operator.

The views expressed in this presentation are those of the author and are not necessarily those of either MISO or PG&E.

Issues that Led to Development of ELMP at MISO

- In MISO's energy markets:
  - Block loaded-resources could be the highest cost energy dispatched but could not be marginal so could not set LMP.
    - Market Monitor recommended developing approaches that would allow block-loaded fast-start resources to set price.
    - Emergency Demand Response (EDR) often dispatched in blocks at very high cost but could not set price.
      - Market would be in shortage condition but could not send shortage price signal since EDR could not set price.
      - FERC ordered MISO to allow EDR to set price.
  - Pricing issues extended beyond block-loaded resources.
    - Similar problems arose for resources whose average cost per MWh decreased as output increased.

Goals for Operation and Pricing

- Commit and dispatch to maximize societal welfare.
  - Maximize value of demand served less cost of supply committed and dispatched.
- Set prices that support commitment and dispatch that were under the ISO's control:
  - A supply would maximize its profit by following ISO's commitment and dispatch if it were paid the nodal energy price,
  - A demand would maximize its net benefit by following ISO's dispatch if it were to be charged the nodal energy price.

Locational Marginal Prices

- Use Security Constrained Unit Commitment (SCUC) to meet efficiency goal.
- Calculate Locational Marginal Prices (LMPs) using the shadow prices of the constraints when commitment-related variables are held fixed at their optimal values.
  - Price using Security Constrained Economic Dispatch (SCED).
  - LMPs do not reflect commitment-related costs.
- LMPs may not meet the goals for prices.
  - LMP may not cover a resource's offer costs at scheduled dispatch.
  - Resource may experience an opportunity cost at scheduled dispatch if it is paid the LMP.

Commitment Related Effects

- Because of commitment related effects, bid-based generator cost curves and demand curves may have non-convex shapes.
- Often cannot set nodal prices that meet the goals.

Revised Goals for Market Operation and Pricing

- Commit and dispatch to maximize societal welfare.
- Set prices that come as close as possible to supporting commitment and dispatch decisions that were determined by the ISO.
  - "Closeness" could be measured by the side payments needed to give participants an incentive to follow commitment and dispatch.
  - Side payments cover
    - Costs not covered by prices,
    - Opportunity costs,
    - Uplift needed to fund transmission rights if congestion rents not sufficient.

Revised Market Processes

- Run the Security Constrained Unit Commitment (SCUC) to commit and dispatch to maximize societal surplus as today.
- Solve the dual of the SCUC to set prices.
  - SCUC considers commitment related costs as well as dispatch costs.
  - Use the shadow prices of the constraints to define the prices, the Extended LMPs (ELMPs).
- The ELMPs meet the pricing goals outlined.

Challenges Faced in Implementing ELMP

Reliably Solving the Dual

- Available commercial optimization software could not be used to reliably solve the dual of the SCUC.
  - The dual is a minimax problem.
    - For given prices, maximize societal surplus over commitment and dispatch, then set prices to minimize result.
  - Developed test software that could solve the dual.
    - Not production grade.
- Developed approximation that could be solved using commercial optimization software.
  - Relax the integer commitment-related variables.
    - Replace the binary variables with continuous variables in [0,1].
  - Testing showed promise.
  - Recent work by Hua and Baldick and by Chao develop conditions under which the relaxation will produce exact ELMPs.

Pricing over Multiple Periods

- SCUC simultaneously optimizes over multiple time periods.
  - Considers inter-temporal constraints:
    - Ramp constraints
    - Minimum up-time constraints on commitments
    - Minimum down-time constraints on commitments
- SCUC's dual simultaneously sets prices over multiple time periods.
  - Costs of actions in one time period may influence the price in another time period.
    - Price in one time period may incorporate costs of actions in later time periods.
    - Price in one time period may incorporate costs of actions in earlier time periods.

Pricing and Settling Across Periods

- Day-Ahead Market is run only once during day.
  - Market is scheduled and intertemporal pricing impacts are calculated once for all periods in the day simultaneously.
- Real-Time Market is re-solved throughout the day.
  - Window for which RT market is re-solved moves throughout day.
    - For a given window, the start of the window is the current period.
  - Costs of potential actions in future periods can influence price in current period.
  - What if costs in the current period influence anticipated prices in a future period in the window?
    - When the window moves to make the future period the new current period, should this be considered in setting the price in the current period?

Pricing and Settling Across Periods in RT Market

- MISO was evaluating different approaches to treat the moving window in the Real-Time Market.
  - When calculating prices in the current time period, ignore costs for actions from before the start of the window.
  - Modify pricing problem formulation to keep prices in prior periods fixed when calculating prices in current and future periods but allow costs for actions from before the window to influence prices.
    - Use a window that starts before the current period in pricing.
  - Calculate prices for settlements in Real-Time Market at the end of the day.
    - Prices calculated in the moving window during the day would be treated as advisory.
- No decision was reached because of the way other challenges were addressed.

Market Software

- Planned to build pricing software using the existing market systems as a base to reduce development risk and cost.
  - Markets scheduled by running SCUC followed by SCED.
- SCUC optimized multiple periods simultaneously.
  - SCUC was run to commit resources.
    - Modeled inter-temporal effects.
    - Treated commitment costs.
    - Only considered a subset of transmission constraints.
    - Modeled losses as fixed.
- SCED optimized each period sequentially.
  - SCED was run to dispatch committed resources in a single period.
    - Optimization did not consider inter-temporal effects.
    - Did not consider commitment costs.
    - Modeled more transmission constraints and marginal losses.

Enhancements Needed to Use SCUC or SCED as Base for ELMP Software

- To develop ELMP software using SCUC software as the base, additional features would have to be incorporated in SCUC model.
  - Additional transmission constraints.
  - Marginal losses.
- To develop ELMP software using SCED software as the base, intertemporal effects would have to be modeled.
  - There was a plan to enhance SCED to optimize over multiple periods simultaneously as in SCUC.
  - Software to solve for prices could then be developed using the multi-period SCED software by adding the relaxed commitment decision variables to SCED.
  - Enhancement of SCED was postponed.

Single Period Pricing Approximation

- SCED models transmission constraints of interest and marginal losses so pricing software was developed using SCED as the base with relaxed commitment variables added.
  - Since SCED only treats decisions in a single period:
    - Amortize start-up cost over a short period after potential decision to start a resource.
    - Treat no-load cost for potential decision to keep a resource on-line in a period in that period.
  - Start-up costs and no-load costs for limited set of resources allowed to affect prices.
    - Fast-start resources – able to have resource on line in limited time after decision to commit, *e.g.* 10 minutes.
    - Resources with limited minimum on-line requirement, *e.g.* 1 hour.
    - This approach also limits potential for adverse market impacts in case unexpected problems arose.

Results and Future Directions

- Testing before implementation indicated acceptable performance of the final approximation.
  - Performance in the market after implementation was acceptable.
- Possible future work:
  - Consider expanding resources covered.
  - Evaluate effects of changing resource mix on exact ELMPs and the approximations.
  - Work on moving closer to exact ELMPs -- possible approaches:
    - Develop multiple period SCED and add relaxed commitment decisions to the enhanced SCED.
    - Add constraints in SCUC and solve SCUC dual directly for ELMPs.

Example of Minimum Cost as Function of Demand in SCUC and the Dual of SCUC

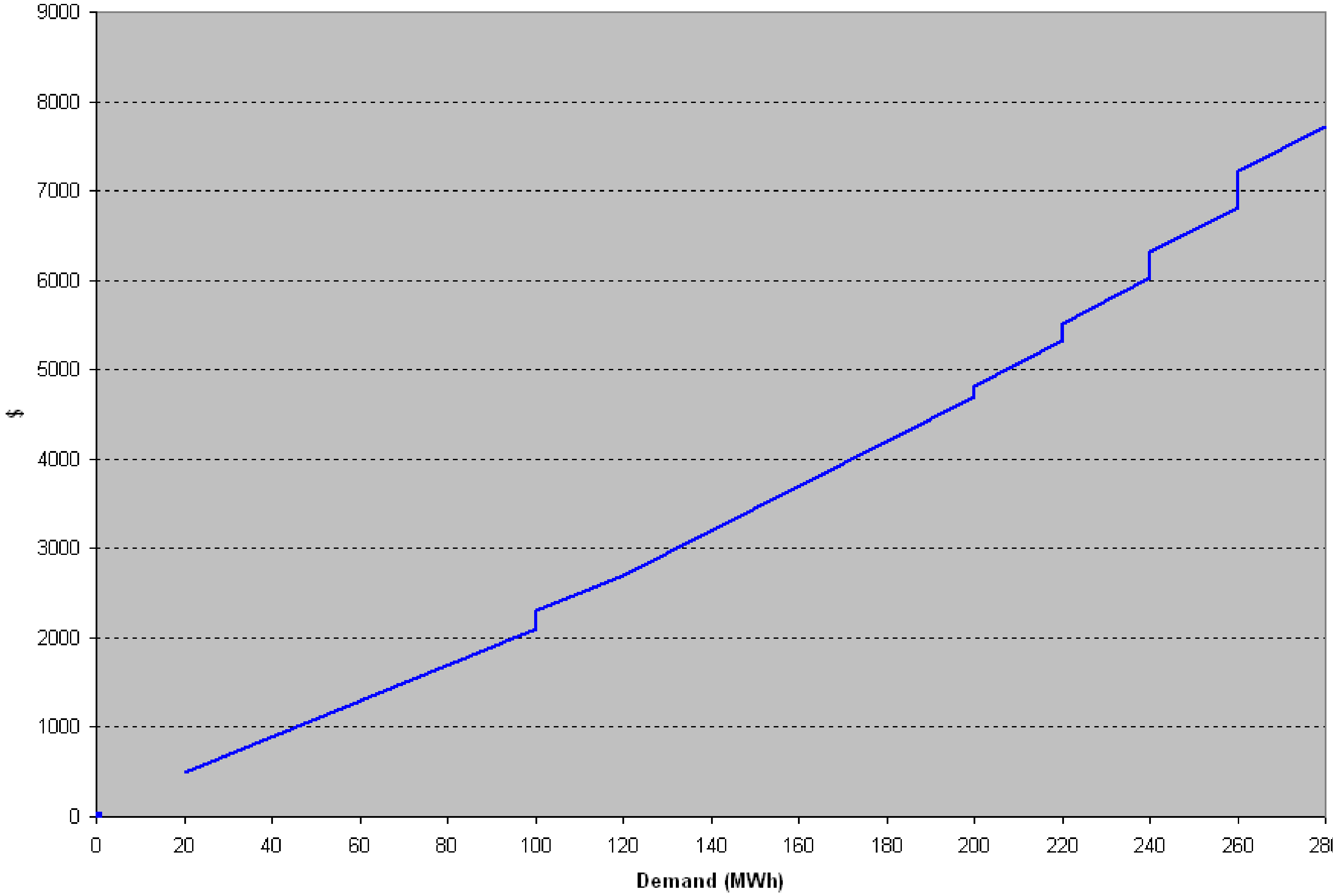
APPENDIX 1

Example Showing the Issue

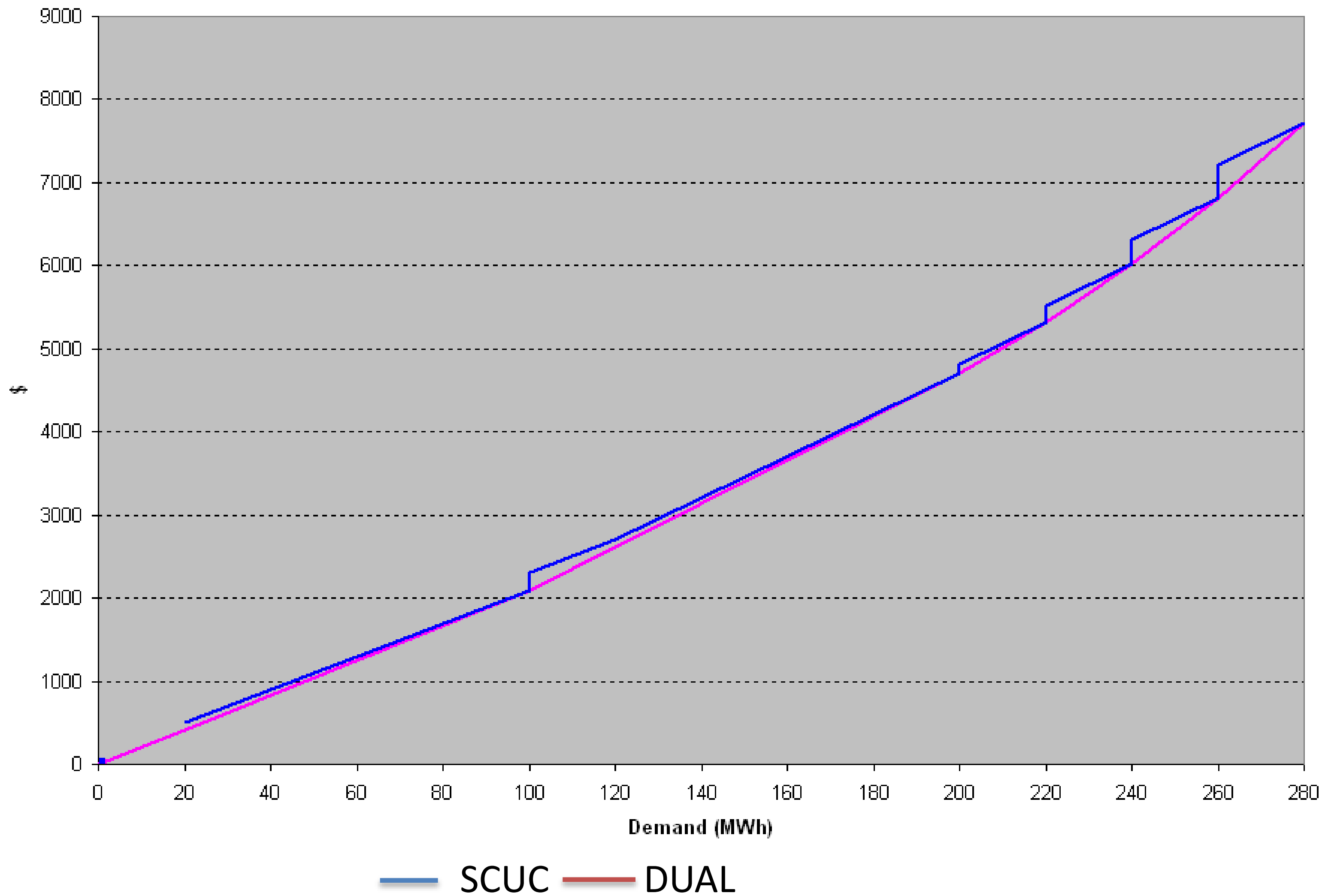
Six generators, single period

	Minimum Dispatch if Committed MW	Maximum Dispatch if Committed MW	Incremental Energy Cost $/MWh	No Load Cost $/hr
G1	20	100	20	100
G2	20	100	25	100
G3	20	20	16	300
G4	20	20	20	300
G5	20	20	10	600
G6	20	20	15	600

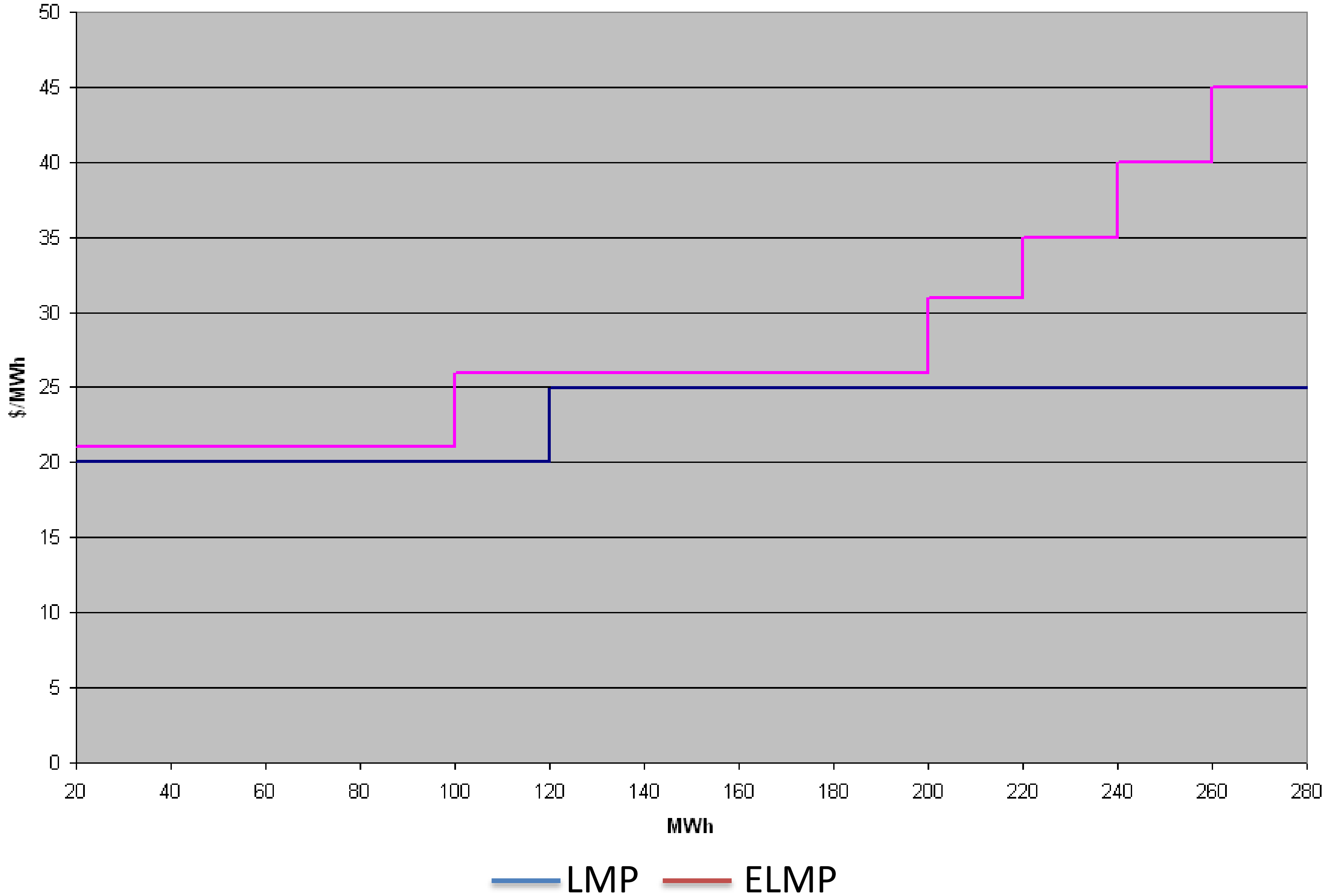
Minimum Cost from SCUC as Function of Demand



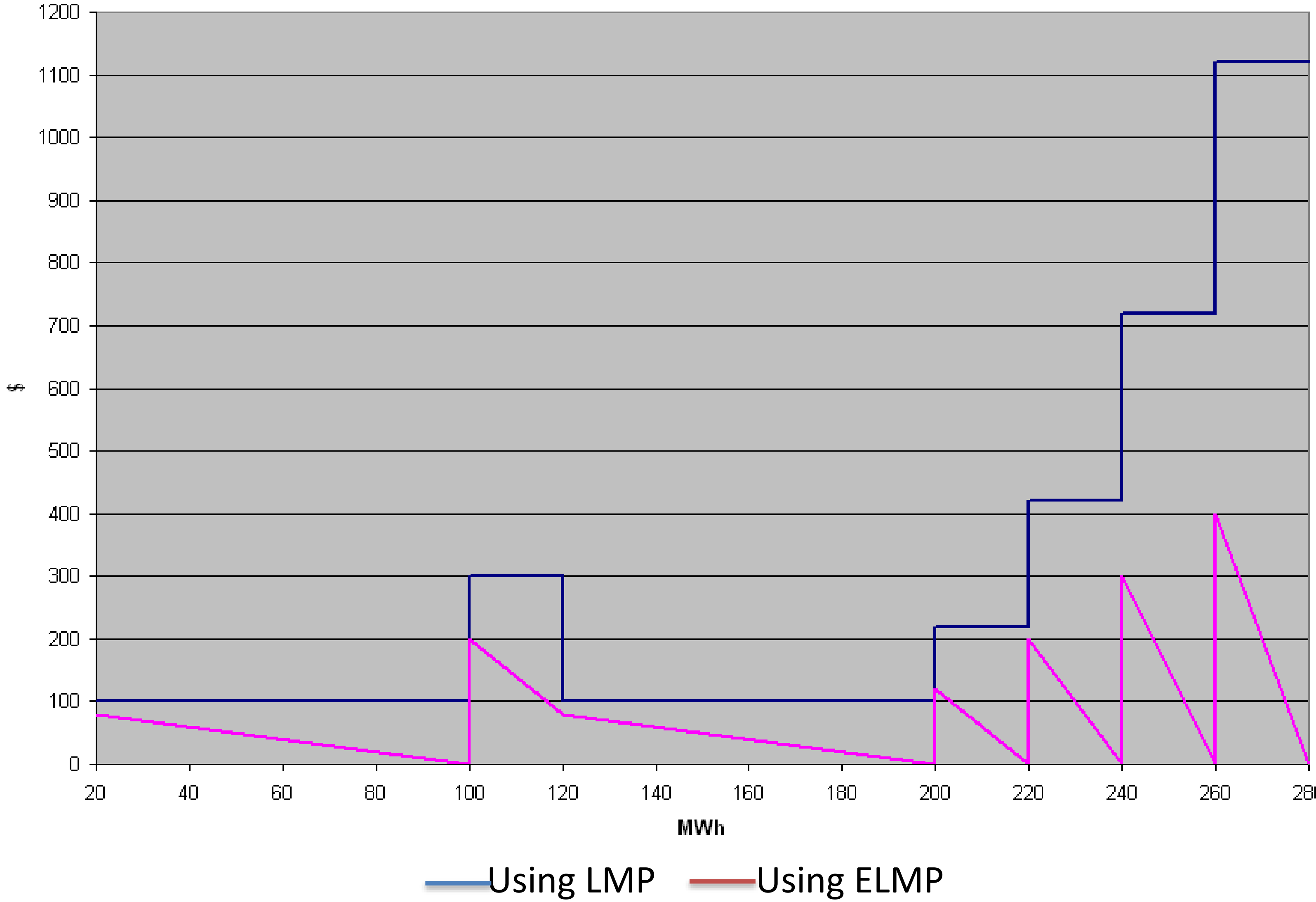
Minimum Cost as Function of Demand from SCUC and its Dual



LMP and ELMP as Function of Demand



Uplift as Function of Demand



Example with Simultaneous Optimization and Pricing over Multiple Periods

APPENDIX 2

Multiple Periods

Each generator must be on-line for a minimum of 2 hours or through the end of the market horizon if committed

	Minimum Dispatch if Committed MW	Maximum Dispatch if Committed MW	Inc. Energy Cost $/MWh	Start Up Cost $	No Load Cost $/hr
G1	20	100	60	0	0
G2	40	100	20	1000	5000

	Demand MW
Hour 1	95
Hour 2	115
Hour 3	135

Efficient Commitment and Dispatch

Two generators and three periods

	Start Up	On Line	Dispatch MWh			LMP $/MWh	ELMP $/MWh
Hour 1 G1	1	1	95				
Hour 1 G2	0	0	0				
Hr 1 Demand			95		Hour 1	60	60
Hour 2 G1	0	1	20				
Hour 2 G2	1	1	95				
Hr 2 Demand			115		Hour 2	20	70
Hour 3 G1	0	1	35				
Hour 3 G2	0	1	100				
Hr 3 Demand			135		Hour 3	60	80

Uplifts

	LMP	ELMP
G1 Make-whole Payment	$800	$0
G1 Opportunity Cost	$0	$2100
G2 Make-whole Payment	$7000	$250
G2 Opportunity Cost	$0	$0
Total Uplift	$7800	$2350

Interesting Property of ELMP

- For a set of requirements (demand, ancillary service requirements, transmission limits), there may not be prices that support efficient commitment and dispatch.
  - However, there will be sets of requirements for which prices will support efficient commitment and dispatch.
  - Those prices are the ELMPs for those sets of requirement.
- We can find a group of requirement sets for which there are common supporting prices such that:
  - The set of requirements of interest is a convex combination of the sets of requirements in the group.
  - The ELMPs for the set of requirements of interest are the common support prices for the group.

Sets of Demands with Supporting Prices

Four sets of hourly demands for which there are common supporting prices with the demand set of interest a convex combination of the four sets.

	Demand Set 1	Demand Set 2	Demand Set 3	Demand Set 4	Common Support Prices
Hour 1	0	100	100	100	60
Hour 2	100	100	100	200	70
Hour 3	100	100	200	200	80

$$0.05 \times \begin{bmatrix} 0 \\ 100 \\ 100 \end{bmatrix} + 0.6 \times \begin{bmatrix} 100 \\ 100 \\ 100 \end{bmatrix} + 0.2 \times \begin{bmatrix} 100 \\ 100 \\ 200 \end{bmatrix} + 0.15 \times \begin{bmatrix} 100 \\ 200 \\ 200 \end{bmatrix} = \begin{bmatrix} 95 \\ 115 \\ 135 \end{bmatrix}$$

$$0.05 + 0.6 + 0.2 + 0.15 = 1$$