Extended Locational Marginal Pricing (Convex Hull Pricing)

Paul Gribik
Li Zhang
Midwest ISO

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Market Clearing Price

- In a market, prices can perform a coordinating function.
  - Producers and consumers react to prices by adjusting their output and consumption.
- Market clearing prices exist if the amount that profit maximizing producers want to produce is equal to that amount that benefit maximizing consumers want to consume at the given prices.
- Prices also determine the distribution of societal surplus to producers and consumers.
  - Market clearing prices, when they exist, allocate societal surplus in such a way that no group could do better by trading among themselves outside the market.

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RTO Electricity Markets

- Most ISOs and RTOs in the US have markets employing:
  - Bid-based day-ahead market schedules based on security constrained day-ahead unit commitment and economic dispatch (SCUC and SCED);
  - Reliability commitment and bid-based security constrained real-time economic dispatch;
  - Locational prices for day-ahead and real-time settlements;
  - Co-optimization of markets for energy and ancillary services to some extent;
  - Financial transmission rights.

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Locational Marginal Pricing

- Locational marginal price (LMP) at a bus is defined as the marginal cost of serving demand at the bus.
  - The cost of serving an infinitesimal increment (or decrement) of demand at the bus using the offers submitted to the market.
  - Commitment cannot change in response to an infinitesimal change in demand.
  - Prices for ancillary services can be similarly defined.
- LMPs are determined in SCED with fixed commitment as set in SCUC.
  - Prices are produced by solving the dual of the SCED problem.
- LMPs in general are not market clearing prices.

LMPs and Market Clearing

- The LMPs produced by SCED are not market clearing prices in general.
  - They do not incorporate start-up costs, no load costs, costs of resources at minimum output, effects of minimum and maximum run times, among other things.
  - As a result, uplift payments may be necessary to give incentives for participants to follow dispatch.
    - Necessary if offer costs at a resource's dispatch point are not covered by prices.
    - Can also arise as opportunity costs if resource's dispatch point is not profit maximizing at the prices.
- Some RTOs have modified the SCED problem used in pricing to try to incorporate some of these effects.

Incorporating Offer Costs in Prices

- What prices would come as close to clearing the market as possible?
  - The uplift needed to give participants incentives to follow dispatch are a measure of how far the prices are from clearing the market.
  - Prices that minimize uplift would come as close as possible to clearing the market by this measure.
- The Security Constrained Unit Commitment Problem considers all offer costs and parameters.
  - Using the dual of the SCUC to set prices would result in prices that incorporate all offer costs.
- The two approaches yield the same set of prices.

Incorporating Offer Costs in Prices

- Since the resulting prices minimize uplift, the pricing approach has been called Minimum Uplift Pricing.
- SCUC implicitly defines Total Cost as a function of the right-hand sides of the constraints in SCUC.
  - The dual to the SCUC problem forms the convex hull of this function and the prices are based on the derivative of the convex hull.
  - The approach has been called Convex Hull Pricing.
- Since the result is extending LMP to incorporate commitment related costs, we call the approach Extended Locational Marginal Pricing (ELMP).
  - ELMP only changes prices. Commitment and dispatch processes are unchanged.

Extended Locational Marginal Pricing

- ELMP would provide an analytically grounded and internally consistent methodology for achieving a number of objectives:
  - Minimizing uplift,
  - Allowing gas turbines and other units operating at their economic minimum or maximum to affect the energy price when appropriate,
  - Allowing emergency demand response that is called in blocks to affect prices when appropriate,
  - Reducing the impact of deviations from an unit optimal commitment on day-ahead prices,
  - Ameliorating real-time price spikes that result from forecasting errors and commitment errors,
  - Prices better aligned with cost causation. If a resource must be committed to meet demand at a location or an AS requirement, corresponding prices may be affected by commitment related costs when appropriate.

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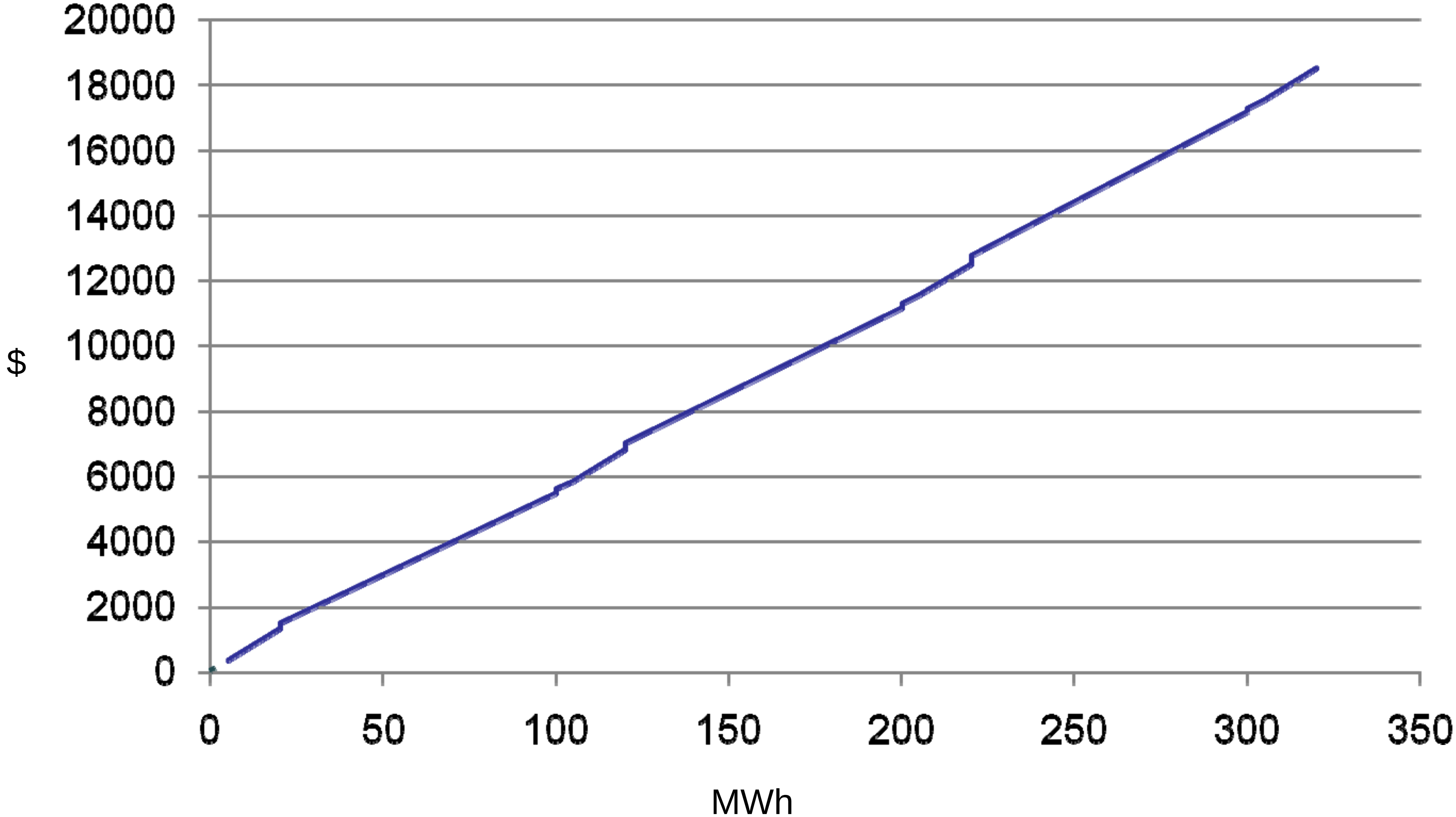
Simple Single Period Energy Only Example

Generator	Min Output if Committed (MW)	Max Output if Committed (MW)	Incremental Offer ($/MWh)	No Load Offer ($/hr)
A	20	100	50	500
B	20	100	52	500
C	20	100	55	500
D	5	20	65	40

Total Cost as Function of Demand



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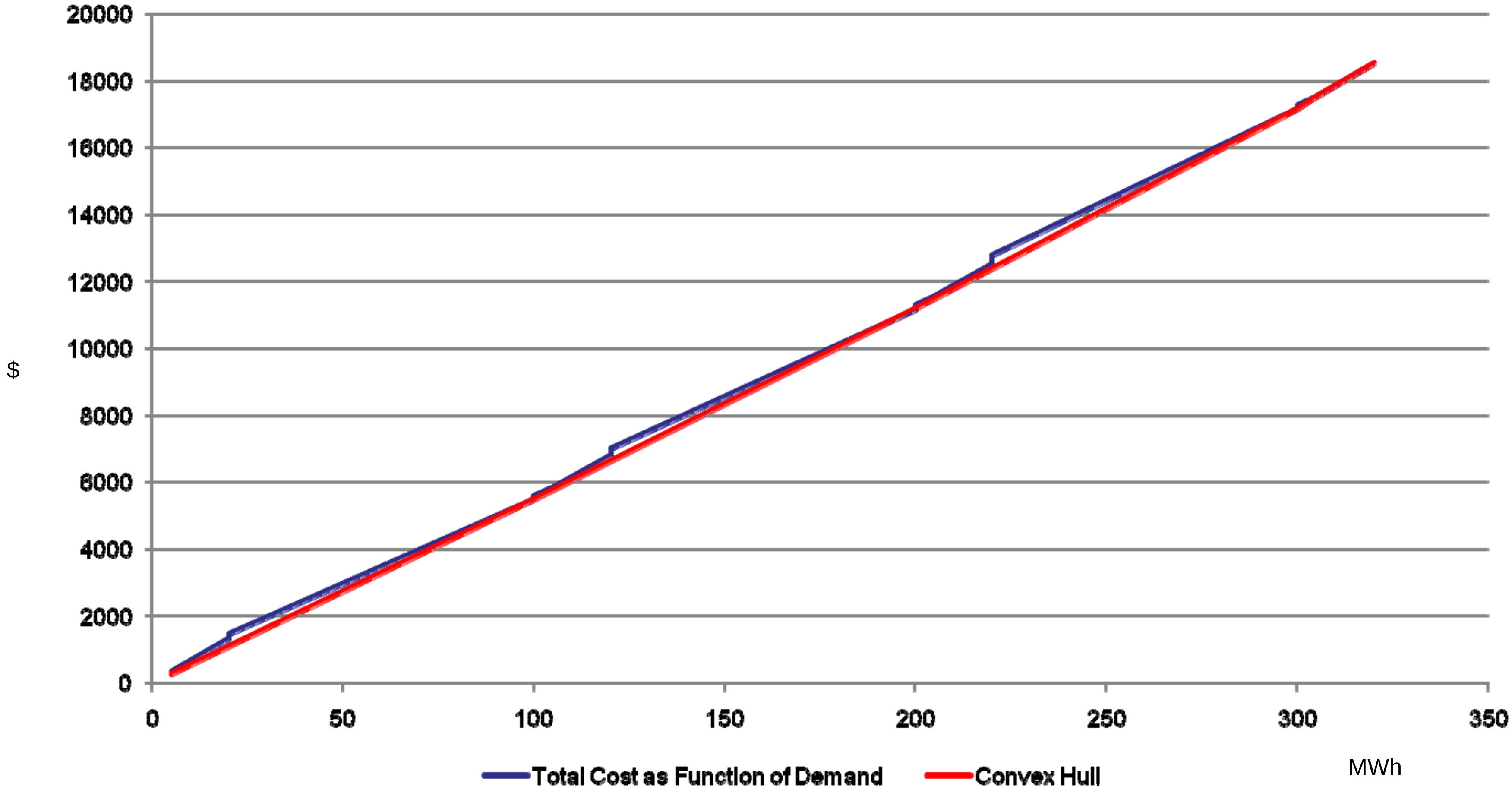
Total Cost Function

- The total cost as a function of demand has ripples in it that make it non-convex.
  - The ripples are caused by changes in the optimal commitment as demand changes.
  - The ripples are small in terms of the total cost at any point.
  - The ripples can have a large impact on the slope, i.e., the incremental cost, at any point and therefore on the LMP.
  - ELMP smoothes out the ripples.
    - In a rough sense, the ELMP is the average change in price calculated based on a demand stepsize that is large enough to remove the non-convexities.

Total Cost and Convex Hull



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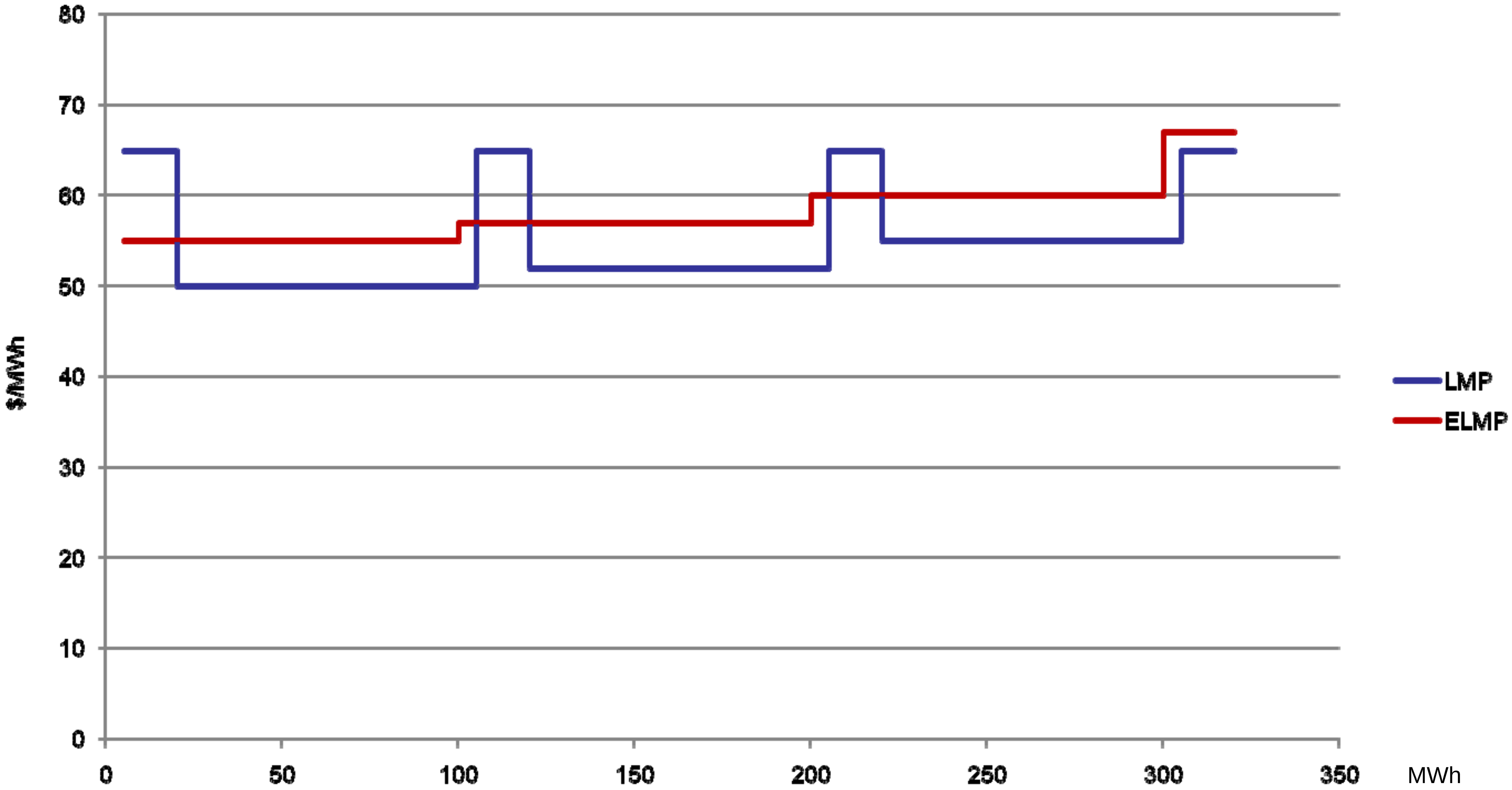
ELMP and LMP



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Cause of the Spikes in LMP

- LMP was higher than ELMP at some demands. For example, for demand between 205 MW and 220 MW.
  - For demand between 120 and 200 MW, it is optimal to commit and dispatch Generators A and B. Above 200 MW, additional capacity must be committed.
  - Between, 200 MW and 220 MW, it is optimal to commit Generator D which has an incremental cost of $65/MWh.
  - Above 220 MW, it is optimal to commit Generator C which has an incremental cost of $55/MWh and not commit Generator D.
  - This change in commitment caused LMP to rise to $65/MWh at 205 MW and drop to $55/MWh at 220 MW.
- ELMP looks at the rate at which total cost changes between 200 MW and 300 MW.
  - This is the average cost of 100 MW from Generator C, or $60/MWh.

Pricing to Reflect Engineering and Economics

- ELMP is a further step in enhancing energy and ancillary services pricing to reflect the physical reality of how costs are incurred in generating electricity.
- Electricity markets will function most efficiently, and with the least ad hoc intervention, when structured to provide prices that are consistent with the underlying cost structure.
  - In order to address this physical reality, generators in most ISO/RTO markets are permitted to make offers for start-up costs, minimum generation (no load) costs, ramp rates (up and down), and minimum and maximum run times, among other things.
  - LMP itself originated in order to reflect the physical reality that congestion costs cause locational differences in prices.
    - LMP incorporates the costs of dispatch in the prices.
    - ELMP incorporates the costs of commitment as well as dispatch in the prices.

(This explanation of ELMP adopts a generation perspective for simplicity, but generalizes to load.)

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Contact Information

- Paul Gribik
  - Sr. Director, Market Development and Analysis
  - pgribik@midwestiso.org
  - 317-249-5146
- Li Zhang
  - Manager, Market Systems Design and Evaluation
  - lzhang@midwestiso.org
  - 317-249-5352