Extended Locational Marginal Pricing (Convex Hull Pricing)

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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.
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.
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.
Simple Single Period Energy Only Example

<table>
<thead>
<tr>
<th>Generator</th>
<th>Min Output if Committed (MW)</th>
<th>Max Output if Committed (MW)</th>
<th>Incremental Offer ($/MWh)</th>
<th>No Load Offer ($/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20</td>
<td>100</td>
<td>50</td>
<td>500</td>
</tr>
<tr>
<td>B</td>
<td>20</td>
<td>100</td>
<td>52</td>
<td>500</td>
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<td>C</td>
<td>20</td>
<td>100</td>
<td>55</td>
<td>500</td>
</tr>
<tr>
<td>D</td>
<td>5</td>
<td>20</td>
<td>65</td>
<td>40</td>
</tr>
</tbody>
</table>
Total Cost as Function of Demand
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

- **Total Cost as Function of Demand**
- **Convex Hull**

$MWh$
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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