LMP Calculation and Uplift

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Session Objectives

• Review fundamentals of locational marginal pricing (LMP) and uplift
• Review simple locational marginal pricing and uplift examples
Components of an Energy Market Offer

Three costs compose a resource’s offer:

- **Start-up cost** ($/start)
- **Incremental energy cost** ($/MWh)
- **No-load cost** ($/hour)
Convexity refers to the curvature of a function.

A function is convex if any straight line you draw across the function does not intersect the function in more than two places.

Non-Convex Function – more than two intersection points

Convex Function – only two intersection points
Locational Marginal Pricing (LMP)

- LMP is the cost of optimally supplying an increment (or decrement) of load at a particular location while satisfying all operational constraints.
  - One can think of the LMP as the change in total production cost to deliver an increment of load at a location using the offers submitted to the market.
  - The commitment cannot change in response to an increment in load.

- LMPs are produced as a result of economic dispatch with the commitment fixed.
LMP Calculation Methodology

• PJM currently uses locational marginal pricing
  – Initially chosen for simplicity in concept and implementation

• It ignores the presence of non-convexities in its price-setting logic and assumes that certain units (often referred to as inflexible units), or certain output ranges of units, are ineligible to set price when they fail the convex condition
  – Many units have non-convex total cost curves because when their output decreases below their minimum operating limits, their incremental costs rise
    • To address this, units submit offers starting at the MW output at which their incremental costs become monotonically increasing
What Resources Can Set LMP?

- In general, resources that are online and being dispatched by PJM can be relied upon to serve the next MW of load (eligible to set LMP)

  *Excludes: block loaded units, interchange transactions, among others*

- From these resources, only those MW above the minimum operating limit may set LMP

Diagram:

- Min MW = Max MW
- Inflexibility: Unit cannot set LMP in this range
What Part of a Resource’s Offer is Used in LMP?

Three Part Offer

1. Startup Offer

- Used in $/Start
- Commitment Decisions
- Dispatch and LMP

2. No Load Offer

- Used in $/Hour

3. Energy Offer Curve

- Used in $/MW
Costs not included in LMP may be recovered via uplift

- For resources that are “out of the money”, any portion of a resource’s incremental cost that exceeds LMP
  - Units that are needed for only a portion of their minimum output
  - “Inflexible” units that are needed to serve load
- Generator start up and no load costs / DR Shutdown cost
What Is Uplift?

Uplift = Make-Whole Payments + Lost Opportunity Cost

- **Make-whole payments**: Occur when a resource’s revenue cannot cover its total offer costs, including fixed costs (start-up and no-load costs).

- **Lost opportunity cost**: Occurs when a resource’s dispatch point is not profit maximizing.
Additional Uplift Drivers

<table>
<thead>
<tr>
<th>Additional Uplift Drivers</th>
<th>Unit Parameters</th>
<th>Load, interchange and outages under or over forecast</th>
<th>Reactive constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Long lead time units</td>
<td></td>
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</tbody>
</table>
LMP AND UPLIFT EXAMPLES

Set 1
We assume no start-up or no-load cost. Each resource is completely flexible.
Example I

Load = 175 MW

Resource A: $60/MWh, 175 MW

Resource B: $80/MWh

Resource C: $100/MWh

Available
Dispatched
Marginal Resource
Example I

Load = 350 MW

- Resource A: 300 MW at $60/MWh
- Resource B: 50 MW at $80/MWh
- Resource C: $100/MWh

Available
- Dispatched
- Marginal
- Resource
Example I

Load = 400 MW

- Resource A: 300 MW, $60/MWh
- Resource B: 100 MW, $80/MWh
- Resource C: Available, $100/MWh

LMP: $80
Example I

Load = 550 MW

$100\text{LMP}$

- **Resource A**: $300\text{ MW}$ at $60\text{$/MWh}$
- **Resource B**: $200\text{ MW}$ at $80\text{$/MWh}$
- **Resource C**: $50\text{ MW}$ at $100\text{/MWh}$

Available

Dispatched

Marginal

Resource
LMP increases and load increases
Example II

What happens if we introduce inflexibility to the resources?

Minimum output the resource can produce when online

- Resource A: 100 MW offer $60/MWh
- Resource B: 100 MW offer $80/MWh
- Resource C: 200 MW offer $100/MWh

Available
Minimum Output
Example II

Load = 350 MW

Resource B needs a make-whole payment of $2,000

Resource A
- 250 MW
- $60/MWh

Resource B
- 100 MW
- $80/MWh

Resource C
- 200 MW
- $100/MWh

Legend:
- Available
- Minimum Output
- Dispatched
- Marginal Resource
Example II

Load = 400 MW

Resource A: 300 MW at $60/MWh
Resource B: 100 MW at $80/MWh
Resource C: 200 MW at $100/MWh

Legend:
- Available
- Minimum Output
- Dispatched
- Marginal Resource
Example II

$60\text{ LMP}$

Load $= 550 \text{ MW}$

Resource B needs a make-whole payment of $2,000$

Resource C needs a make-whole payment of $8,000$
Price Formation Curve

- Completely flexible
- Parameter restrictions
Price Formation Curve using Units A, B & C

Load $\leq 300$ MW

Unit A is the only unit online and it is marginal.
Price Formation Curve using Units A, B & C

Unit Dispatch
- Unit A: $60
- Unit B: $80
- Unit C: $100

Production costs jump as the cost of bringing Unit B online is incurred, yet LMP does not change.
Price Formation Curve using Units A, B & C

$0 \leq \text{Load} \leq 400$ MW

Unit A and B are both on. Unit A is fully loaded at 300 MW. Unit B is now marginal for energy and therefore sets LMP.

400 MW < Load ≤ 500 MW

Unit A and B are both on. Unit A is fully loaded at 300 MW. Unit B is now marginal for energy and therefore sets LMP.
500 MW < Load ≤ 600 MW

Unit A, B and C are all on. Both Unit A and B are reduced by 100 MW to accommodate the min. of Unit C. Unit A is marginal as it provides the next cheapest MW.

Production cost jumps again as Unit C is brought online, yet LMP has dropped.
Price Formation Curve using Units A, B & C

Production Cost ($) $/MWh

MW of Load

$0 $20,000 $40,000 $60,000 $80,000 $100,000 $120,000

$40 $50 $60 $70 $80 $90 $100 $110 $120

0 100 200 300 400 500 600 700 800 900 1000

Unit Dispatch

Unit A: $60
Unit B: $80
Unit C: $100

600 MW < Load <= 700 MW
Same as previous but now Unit A has been fully dispatched. Unit B now marginal. Unit C still sitting at min.
Price Formation Curve using Units A, B & C

Load > 700 MW
Units A and B at max. Unit C is marginal and setting LMP.
LMP AND UPLIFT EXAMPLES

Set 2
Example 5: Base Scenario

Hour 1

LMP = $35/MWh

Load = 700 MW

- Unit D: $35 200 MW
- Unit C: $30 200 MW
- Unit B: $25 200 MW
- Unit A: $10 200 MW

Units A and D are flexible
Units B and C are lumpy or block-loaded
Minimum Runtime = 1 hour

Hour 2

LMP = $35/MWh

Load = 700 MW

- Unit D: $35 200 MW
- Unit C: $30 200 MW
- Unit B: $25 200 MW
- Unit A: $10 200 MW
Example 5: Declining Demand

Load = 700 MW

Units A and D are flexible
Units B and C are lumpy or block-loaded
Minimum Runtime = 1 hour

Hour 1
LMP = $35/MWh

- Unit D: $35
  - 200 MW
- Unit C: $30
  - 200 MW
- Unit B: $25
  - 200 MW
- Unit A: $10
  - 200 MW

Load = 500 MW

Hour 2
LMP = $35/MWh

- Unit D: $35
  - 200 MW
- Unit C: $30
  - 200 MW
- Unit B: $25
  - 200 MW
- Unit A: $10
  - 200 MW
Example 5: Unit C has an Incentive to Bid Inflexibly

Units A and D are flexible
Units B and C are lumpy or block-loaded
Minimum Runtime = 1 hour

**Hour 1**

LMP = $35/MWh

- Unit D: $35, 200 MW
- Unit C: $30, 200 MW
- Unit B: $25, 200 MW
- Unit A: $10, 200 MW

**Hour 2**

LMP = $35/MWh

- Unit D: $35, 200 MW
- Unit C: $30, 200 MW
- Unit A: $10, 200 MW
- Unit B: $25, 200 MW

Unit C raises its Minimum Runtime to 2 hours and replaces Unit B

Load = 700 MW

Load = 500 MW
Example 5: Units B & C have an Incentive to Bid Inflexibly

**Hour 1**
LMP = $35/MWh

- **Unit D**: $35 200 MW
- **Unit C**: $30 200 MW
- **Unit B**: $25 200 MW
- **Unit A**: $10 200 MW

Load = 700 MW

- Units A and D are flexible
- Units B and C are lumpy or block-loaded
- Minimum Runtime = 1 hour

**Hour 2**
LMP = $10/MWh
Uplift = $4,000

- **Unit C**: $30 200 MW
- **Unit B**: $25 200 MW
- **Unit A**: $10 200 MW
- **Unit D**: $35 200 MW

Load = 500 MW

- Both units B and C raise their Minimum Runtime to 2 hours and are dispatched
APPENDIX
LMP AND UPLIFT EXAMPLES

Set 3
Example #1

- Load = 480 MW
- No imports, exports or price-sensitive demand
- Can be considered in the context of the Day-Ahead or Real-Time Market
- Objective: to determine the least-cost commitment and dispatch to meet the load

Note: The following numerical example was initially developed by ISO New England and is used with permission. 
Example #1: Offer Blocks (MW)

Any resource that is “committed” must run at least at its minimum.
Example #1: Marginal Pricing with Minimum Generation

- **Resource W**: 200 MW @ $50
- **Resource X**:
  - 30 MW @ $53
  - 30 MW @ $56
  - 100 MW @ $60
  - 40 MW @ $65
- **Resource Y**:
  - 40 MW @ $69
  - 50 MW @ $200
  - 50 MW @ $221
  - 50 MW @ $241

Minimum generation indicated by red arrow.
Example #1: What Is the Commitment and Dispatch?

Load = 480 MW

- **Cleared MW**
  - Resource W: 200 MW @ $50
  - Resource X: 30 MW @ $56
  - Resource X: 40 MW @ $65
  - Resource X: 50 MW @ $69
  - Resource Y: 10 MW @ $69
  - Resource Y: 50 MW @ $200
  - Resource Y: 50 MW @ $221
  - Resource Y: 50 MW @ $241

- **Not Cleared MW**
  - Resource X: 30 MW @ $53
  - Resource Y: 10 MW @ $69

- **Minimum**
  - Minimum Load = 480 MW
Example #1: What Is the Commitment and Dispatch?

- **Cleared MW**
  - 200 MW @ $50
  - 30 MW @ $53
  - 30 MW @ $56
  - 100 MW @ $60
  - 40 MW @ $65
  - 30 MW @ $69
  - 10 MW OT @ $69
  - 50 MW @ $200
  - 50 MW @ $221
  - 50 MW @ $241

- **Not Cleared MW**

- **Minimum**

- **Make-Whole Payment**

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<table>
<thead>
<tr>
<th>$/MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW</td>
</tr>
</tbody>
</table>

**Resource W**

- 200 MW @ $50

**Resource X**

- 30 MW @ $53
- 30 MW @ $56
- 100 MW @ $60
- 40 MW @ $65
- 30 MW @ $69
- 10 MW OT @ $69

**Resource Y**

- 50 MW @ $200
- 50 MW @ $221
- 50 MW @ $241
Example #1: Pricing and Settlement

The settlement:

\[ \text{LMP} = \$69/\text{MWh} \]

<table>
<thead>
<tr>
<th>Resource</th>
<th>Commitment</th>
<th>Dispatch (MW)</th>
<th>Total Offer Cost ($)</th>
<th>Payment ($)</th>
<th>MWP ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>On</td>
<td>260</td>
<td>13,270</td>
<td>17,940</td>
<td>0</td>
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<tr>
<td>X</td>
<td>On</td>
<td>170</td>
<td>10,670</td>
<td>11,730</td>
<td>0</td>
</tr>
<tr>
<td>Y</td>
<td>On</td>
<td>50</td>
<td>10,000</td>
<td>3,450</td>
<td>6,550</td>
</tr>
</tbody>
</table>

Y has an incentive to deviate from the 50 MW dispatch (it would prefer 0 MW given the $69/MWh price) without the make-whole payment.
Example #2

- Load = 365 MW
- Same offer blocks as Example #1 for each resource
- Fixed costs (start-up) added to Resource X and Resource Y
Example #2: Offer Blocks (MW) & Fixed Costs

Any resource that is “committed” must run at least at its minimum cost.
The Commitment and Dispatch: Example #2

Load = 365 MW

Resource W
- 200 MW @ $50
- 30 MW @ $53

Resource X (Start-up $30k)
- 30 MW @ $56
- 100 MW @ $60
- 40 MW @ $65
- 40 MW @ $69

Resource Y (Start-up $5k)
- 50 MW @ $200
- 50 MW @ $221
- 5 MW @ $241
- 45 MW @ $241

$/MWh

Cleared MW
Not Cleared MW
Minimum
The Commitment and Dispatch: Example #2

Load = 365 MW

Resource W
- 200 MW @ $50
- 30 MW @ $53

Resource X (Start-up $30k)
- 30 MW @ $56
- 100 MW @ $60
- 40 MW @ $65
- 40 MW @ $69

Resource Y (Start-up $5k)
- 50 MW @ $200
- 50 MW @ $221
- 5 MW @ $241

$241

$/MWh
definitions:
- Cleared MW
- Not Cleared MW
- Minimum
Example #2: Pricing and Settlement

The **LMP is $241/MWh.**

<table>
<thead>
<tr>
<th>Resource</th>
<th>Commitment</th>
<th>Dispatch (MW)</th>
<th>Total Offer Cost ($)</th>
<th>Payment ($)</th>
<th>MWP ($)</th>
<th>LOC ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>On</td>
<td>260</td>
<td>13,270</td>
<td>62,660</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X</td>
<td>Off</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2,020</td>
</tr>
<tr>
<td>Y</td>
<td>On</td>
<td>105</td>
<td>27,255</td>
<td>25,305</td>
<td>1,950</td>
<td>0</td>
</tr>
</tbody>
</table>

**Reminder:** At X’s offer prices of $60–$69/MWh, it would want to come online at a $241/MWh clearing pricing since it would make a profit at $241/MWh of $2,020. Today’s markets in general do not pay this LOC to offline resources.
What if the Load Went Up for this Example?

• As total load rises, the total offer cost of meeting that demand rises.

• Increase load to:
  – Example 3 – Load = 430 MW
  – Example 4 – Load = 445 MW
The Commitment and Dispatch: Example #3

Load = 430 MW

Resource W
- 200 MW @ $50
- 30 MW @ $53
- 30 MW @ $56

Resource X (Start-up $30k)
- 100 MW @ $60
- 40 MW @ $65
- 30 MW @ $69

Resource Y (Start-up $5k)
- 10 MW @ $69
- 50 MW @ $200
- 50 MW @ $221
- 50 MW @ $241

$/MWh

Cleared MW
Not Cleared MW
Minimum
The Commitment and Dispatch: Example #3

Load = 430 MW
The **LMP** is **$69/MWh**.

Example #3: Pricing and Settlement

<table>
<thead>
<tr>
<th>Resource</th>
<th>Commitment</th>
<th>Dispatch (MW)</th>
<th>Total Offer Cost ($)</th>
<th>Payment ($)</th>
<th>MWP ($)</th>
<th>LOC ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>On</td>
<td>260</td>
<td>13,270</td>
<td>17,940</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X</td>
<td>On</td>
<td>170</td>
<td>40,670</td>
<td>11,730</td>
<td>28,940</td>
<td>0</td>
</tr>
<tr>
<td>Y</td>
<td>Off</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
The Commitment and Dispatch: Example #4

Load = 445 MW

Resource W
- 200 MW @ $50
- 30 MW @ $53
- 30 MW @ $56

Resource X (Start-up $30k)
- 100 MW @ $60
- 35 MW @ $65

Resource Y (Start-up $5k)
- 69 MW @ $65
- 5 MW @ $69
- 50 MW @ $200
- 50 MW @ $221
- 50 MW @ $241

$/MWh

Cleared MW
Not Cleared MW
Minimum
The Commitment and Dispatch: Example #4

Load = 445 MW

Resource W
- 0 MW @ $0
- 30 MW @ $53
- 100 MW @ $60

Resource X (Start-up $30k)
- 30 MW @ $56
- 35 MW @ $65
- 5 MW @ $65

Resource Y (Start-up $5k)
- 69 MW @ $9
- 50 MW @ $200
- 50 MW @ $221
- 50 MW @ $241

Minimum Cost: $65
Example #4: Pricing and Settlement

The **LMP** is $65/MWh:

<table>
<thead>
<tr>
<th>Resource</th>
<th>Commitment</th>
<th>Dispatch (MW)</th>
<th>Total Offer Cost ($)</th>
<th>Payment ($)</th>
<th>MWP ($)</th>
<th>LOC ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>W</strong></td>
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<td>260</td>
<td>13,270</td>
<td>16,900</td>
<td>0</td>
<td>0</td>
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<tr>
<td><strong>X</strong></td>
<td>On</td>
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<td>38,275</td>
<td>8,775</td>
<td>29,500</td>
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<td>15,000</td>
<td>3,250</td>
<td>11,750</td>
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</table>
Summary of Examples #2-4

- In Examples 2-4, the price decreases as load increases

<table>
<thead>
<tr>
<th>Load (MW)</th>
<th>LMP ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>365</td>
<td>241</td>
</tr>
<tr>
<td>430</td>
<td>69</td>
</tr>
<tr>
<td>445</td>
<td>65</td>
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</tbody>
</table>