Locational Marginal Pricing Components
Agenda

- LMP Components
- 5 Bus Model
- Shadow Prices
- Statistics
- LMP Simulation Demo
What is LMP?

• Pricing method PJM uses to:
  – price energy purchases and sales in PJM Market
  – price transmission congestion costs to move energy within PJM RTO
  – price losses on the bulk power system
How does PJM Use LMP?

- Generators get paid at generation bus LMP
- Loads pay at load bus LMP
- Transactions pay differential in source and sink LMP
System Marginal Price (SMP)

- Incremental price of energy for the system, given the current dispatch, at the load weighted reference bus
  - SMP is LMP without losses or congestion
- Same price for every bus in PJM (no locational aspect)
- Calculated both in day ahead and real time
Locational Marginal Price

\[ \text{LMP} = \text{System Marginal Price} + \text{Congestion Component} + \text{Marginal Loss Component} \]

- **Congestion Component (CLMP)**
  - Represents price of congestion for binding constraints
    - Calculated using the Shadow Price
  - Will be zero if no constraints (Unconstrained System)
    - Will vary by location if system is constrained
  - Used to price congestion
    - Load pays Congestion Price
    - Generation is paid Congestion Price
  - Calculated both in day ahead and real time
**Operational Limits**

- **Thermal Limits** - Thermal limits are due to the thermal capability of power system equipment

- **Voltage Limits** - Utility and customer equipment is designed to operate at a certain supply voltage

- **Stability Limits** - Refers to the power system maintaining a state of equilibrium
Control Actions

• There are three basic types of actions that can be performed to control the flow of power on the electric system:

1. System Reconfiguration
2. Transaction Curtailments
3. Redispach Generation
When Constraints Occur...

- Delivery limitations prevent use of “next least-cost generator”
- Higher-cost generator closer to load must be used to meet demand
- Cost expressed as “security constrained redispatch cost”
Security Constrained Re-Dispatch

Control Area
Constrained System

Low Cost Generator
$$

High Cost Generator
$$$$

Higher cost Generator more advantageously located relative to transmission system limit

Transmission “Bottleneck” or Constraint
Congestion effects on LMP and Revenues

• When the bus is upstream of a constraint
  – Congestion Component is negative
  – Results in negative revenues to unit

• When the bus is downstream of a constraint
  – Congestion Component is positive
  – Results in positive revenues to unit
Constraints & Marginal Units

- There will always be at least one marginal unit
  - System Energy Unit
- There will be an additional marginal unit for each binding constraint
- It is possible and, in fact likely, that there will be multiple marginal units for a given time interval
Marginal Loss Component (MLMP)

- Represents price of marginal losses
  - Transmission losses are priced according to marginal loss factors which are calculated at a bus and represent the percentage increase in system losses caused by a small increase in power injection or withdrawal
    - Calculated using penalty factors
- Will vary by location
- Used to price losses
  - Load pays the Loss Price
  - Generation is paid the Loss Price
- Calculated both in day-ahead and real-time
Marginal Loss effects on LMP and Revenues

• When the bus is electrically distant from the load
  – Marginal Loss Component is negative
  – Results in negative revenues to unit

• When the bus is electrically close to the load
  – Marginal Loss Component is positive
  – Results in positive revenues to unit
What would you expect to see?

Congestion Component of LMP?
Loss Component of LMP?

Congestion Component of LMP? (+) (-)
Loss Component of LMP? (-) (+)
Agenda

• LMP Components
• 5 Bus Model
• Shadow Prices
• Statistics
• LMP Simulation Demo
LMP Examples

5-Bus Model Examples

- 600 MW $10/MWh
  - Brighton

- 230 MW Thermal Limit

- 200 MW $40/MWh
  - Sundance

- 520 MW $30/MWh
  - Solitude

- 110 MW $14/MWh
  - Alta

- 100 MW $15/MWh
  - Park City

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Example # 1 - 5 Bus Transmission Grid

Generator Offers

- 600 MW, $10/MWh (Brighton)
- 110 MW, $14/MWh (Alta)
- 100 MW, $15/MWh (Park City)

Sundance
- 200 MW, $40/MWh
- 223 MW

Solitude
- 520 MW, $30/MWh
- 223 MW

System Loads = 669 MW
System Losses = 17 MW
Example #1 - 5 Bus Transmission Grid

Dispatch & Energy Flow

System Loads = 669 MW
System Losses = 17 MW

<table>
<thead>
<tr>
<th>Plant</th>
<th>MW</th>
<th>Price/MWh</th>
<th>PF</th>
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<tbody>
<tr>
<td>Solitude</td>
<td>520</td>
<td>30</td>
<td>1.0000</td>
</tr>
<tr>
<td>Sundance</td>
<td>200</td>
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</tr>
<tr>
<td>Park City</td>
<td>223</td>
<td>15</td>
<td>1.0492</td>
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<tr>
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<td>223</td>
<td>14</td>
<td>1.0492</td>
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<tr>
<td>Alta</td>
<td>86</td>
<td>10</td>
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<tr>
<td>Brighton</td>
<td>600</td>
<td>10</td>
<td>1.0625</td>
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</table>

System Loads = 669 MW
System Losses = 17 MW

PF = 1.0492
PF = 1.0492
PF = 1.0625
PF = 1.0000
PF = 1.0247

7/13/2017
LMP Calculations

• **System Energy Price** = LMP at the Reference Bus (where Congestion & Losses = 0)

• **Reference or “Slack” Bus** is the “electrical load center” of the system

• **Losses** are calculated using the System Energy Price & the Penalty Factor ($Pf$)
### Example #1 - Summary

<table>
<thead>
<tr>
<th>Unit</th>
<th>Offer Price</th>
<th>Penalty Factor</th>
<th>Adjusted Offer</th>
<th>System Energy Price</th>
<th>Loss Price</th>
<th>Congestion Price</th>
<th>Total LMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brighton</td>
<td>$10.00</td>
<td>1.0625</td>
<td>$10.625</td>
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<td>-$0.86</td>
<td>$0.00</td>
<td>$13.83</td>
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<td>$14.00</td>
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<td>1.0000</td>
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<td>$0.00</td>
<td>$14.33</td>
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</table>

- **Marginal Unit**
- **Reference Bus**

**Notes:**
- System Energy Price and Loss Price are adjusted based on the offer price and penalty factor.
- Loss and Congestion Components of LMP are “0” at the Reference Bus.

Unconstrained System:

- **Unit Running**
- **Unit Not Running**
Example # 1 - 5 Bus Transmission Grid

**LMPs**

**Area Load** = 669  
**Area Losses** = 17 MW  
**Area Generation** = 686

**LMP = $13.83**

- **Brighton**  
  - 600 MW  
  - $10/MWh  
  - PF = 1.0625

**LMP = $14.00**

- **Alta**  
  - 110 MW  
  - $14/MWh  
  - PF = 1.0492

**LMP = $14.33**

- **Sundance**  
  - 200 MW  
  - $40/MWh  
  - PF = 1.0247

**LMP = $14.69**

- **Solitude**  
  - 520 MW  
  - $30/MWh  
  - PF = 1.000

**Marginal Unit**  
**Reference Bus**
Agenda

• LMP Components
• 5 Bus Model

• Shadow Prices

• Statistics
• LMP Simulation Demo
Binding Constraints and Shadow Prices

• Binding constraints limit the ability to improve the objective function
  – If a binding constraint is relaxed, or made less restrictive, a better solution is possible

• The shadow price is the marginal improvement caused by relaxing the constraint
  – In energy markets, a shadow price shows the savings in Bid Production Cost if binding constraint is relaxed by 1MW

• Shadow prices tell us how much more money we can make (or save) by improving one of our limiting factors or boundary conditions
Shadow Price

**Area 1**
- ON: G1, G2, G4
- OFF: G5
- Load = 200MW
- Limit = 400MW
- $60

**Area 2**
- ON: G3
- Load = 600MW
- $90

Total Production Cost = (600*60) + (200*90) = $54,000
**Shadow Price**

**Area 1**
- G1: ON
- G2: ON
- G4: ON
- OFF: G5

**Area 2**
- G3: ON

Limit = 401MW

Load = 200MW

Load = 600MW

**Total Production Cost** = $(601 \times 60) + (199 \times 90) = 53,970$
Shadow Prices

• (Before: 400 MW limit) Total production cost is $54,000
• (After: 401 MW limit) Total production cost is $53,970
• “Relaxing” constraint limit by 1 MW saved us $30 in total production costs
• Difference between the “Before” and “After” case is the Shadow price = $30
LMP Components

System Energy Price

System Energy Price

Marginal loss Sensitivity factor

Constraint\textsubscript{A} Shadow Price

DFAX\textsubscript{A}

System Energy Price =

Marginal Loss Component

Congestion Component\textsubscript{A} =

LMP
Which constraints does raising unit output help?
Which constraints does raising unit output hurt?
Is close to center of system load?

**Bonus Question – How many marginal units does this system have?**
### System Energy Component

<table>
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<tr>
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<th>System Energy Price</th>
<th>X</th>
<th>* 1.0</th>
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<th>System Energy Component</th>
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<tbody>
<tr>
<td>System Energy Component</td>
<td>$33.11</td>
<td>X</td>
<td>1.0</td>
<td>=</td>
<td>$33.11</td>
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</table>

### Loss Component

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<th>Marginal Loss Sensitivity Factor</th>
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<th>Marginal Loss Component</th>
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<td>X</td>
<td>-0.0315</td>
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### Congestion Components

<table>
<thead>
<tr>
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<th>=</th>
<th>Congestion Component</th>
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</thead>
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<tr>
<td>Constraint A</td>
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<td>Constraint B</td>
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<td>=</td>
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<td>=</td>
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<td>Constraint D</td>
<td>-$5.48</td>
<td>X</td>
<td>-0.0200</td>
<td>=</td>
<td>$0.11</td>
</tr>
</tbody>
</table>

**LMP =** $39.23

- Which constraints does raising unit output help? **Constraints A, C and D**
- Which constraints does raising unit output hurt? **Constraint B**
- Is close to center of system load? **No**
- **Bonus Question – How many marginal units does this system have?** 5
Example # 2 - 5 Bus Transmission Grid

Constrained System Loads + Losses = 921

- Brighton (600 MW, $10/MWh)
- Alta (110 MW, $14/MWh)
- Park City (100 MW, $15/MWh)
- Sundance (200 MW, $40/MWh)
- Solitude (520 MW, $30/MWh)

Loads = 300 MW
Example # 2 - 5 Bus Transmission Grid

Dispatch Solution Ignoring Thermal Limit

System Loads = 900 MW
System Losses = 21 MW

Dispatched at 600 MW
Brighton

600 MW
$10/MWh

Dispatched at 110 MW
Alta

110 MW
$14/MWh

Dispatched at 100 MW
Park City

100 MW
$15/MWh

Dispatched 110 MW
Solitude

200 MW
$40/MWh

300 MV

520 MW
$30/MWh

Dispatched 100 MW
300 MV

230 MW Thermal Limit

193

342

355

48

144

258

32
Example #2 - 5 Bus Transmission Grid

Actual Dispatched Generation

- **Dispatched at 509 MW**
  - **Brighton**: 600 MW, $10/MWh
  - **Alta**: 110 MW, $14/MWh, Dispatched at 110 MW
  - **Park City**: 100 MW, $15/MWh, Dispatched at 100 MW

- **System Loads = 900 MW**
- **System Losses = 15 MW**

- **Dispatched at 196 MW**
  - **Solitude**: 520 MW, $30/MWh
  - **200 MW**: at $40/MWh

- **Thermal Limit**: 230 MW

Dispatched generation:
- **E**: 230 MW
- **D**: 224 MW
- **B**: 308 MW
- **C**: 101 MW
- **A**: 180 MW

Generated at:
- **D**: 300 MW
- **A**: 100 MW
- **C**: 300 MW
- **B**: 300 MW

Actual dispatched generation: 509 MW from **E**

Dispatched at 196 MW: **Solitude**

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Calculate Shadow Price and Congestion Price

Production Cost calculated using a DC Power Flow Solution

<table>
<thead>
<tr>
<th>Unit</th>
<th>MW</th>
<th>Price</th>
<th>No Load</th>
<th>Production Cost</th>
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</thead>
<tbody>
<tr>
<td>Brighton</td>
<td>485</td>
<td>10</td>
<td>$399.80</td>
<td>$5,249.80</td>
</tr>
<tr>
<td>Alta</td>
<td>110</td>
<td>14</td>
<td>$100.00</td>
<td>$1,640.00</td>
</tr>
<tr>
<td>Park City</td>
<td>100</td>
<td>15</td>
<td>$100.00</td>
<td>$1,600.00</td>
</tr>
<tr>
<td>Solitude</td>
<td>205</td>
<td>30</td>
<td>$100.00</td>
<td>$6,250.00</td>
</tr>
<tr>
<td>Sundance</td>
<td>0</td>
<td>40</td>
<td>$100.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>900</td>
<td></td>
<td></td>
<td>$14,739.80</td>
<td></td>
</tr>
</tbody>
</table>

Production Cost with 231 MW across Brighton - Sundance line

<table>
<thead>
<tr>
<th>Unit</th>
<th>MW</th>
<th>Price</th>
<th>No Load</th>
<th>Production Cost</th>
</tr>
</thead>
<tbody>
<tr>
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<td>$1,640.00</td>
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<td>Park City</td>
<td>100</td>
<td>15</td>
<td>$100.00</td>
<td>$1,600.00</td>
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<td>Solitude</td>
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<tr>
<td>900</td>
<td></td>
<td></td>
<td>$14,679.80</td>
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</table>

Shadow Price = $14,679.80 - $14,739.80 = -$60.00

<table>
<thead>
<tr>
<th>Bus</th>
<th>Monitored Line</th>
<th>DFAX</th>
<th>Shadow Price</th>
<th>Congestion Price</th>
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<tbody>
<tr>
<td>Brighton</td>
<td>Brighton - Sundance</td>
<td>0.307167</td>
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<td>-$18.43</td>
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<td>Alta</td>
<td>Brighton - Sundance</td>
<td>0.199167</td>
<td>-$60.00</td>
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<td>Park City</td>
<td>Brighton - Sundance</td>
<td>0.199167</td>
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<tr>
<td>Solitude</td>
<td>Brighton - Sundance</td>
<td>0</td>
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<tr>
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PJM©2017 34 7/13/2017
<table>
<thead>
<tr>
<th>Unit</th>
<th>Offer Price</th>
<th>Penalty Factor</th>
<th>Adjusted Offer</th>
<th>System Energy Price</th>
<th>Loss Price</th>
<th>Congestion Price (Shadow Price * DFAX)</th>
<th>Total LMP</th>
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<tbody>
<tr>
<td>Brighton</td>
<td>$10.00</td>
<td>1.0553</td>
<td>$10.5530</td>
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<td>$39.35</td>
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### Notes:

- **Marginal Unit**
- **Reference Bus**

- **Unit Running**
- **Unit Not Running**

Loss and Congestion Components of LMP are “0” at the Reference Bus
Agenda

- LMP Components
- 5 Bus Model
- Shadow Prices
- Statistics
- LMP Simulation Demo
# Table 3-75 Day-ahead and real-time average LMP (Dollars per MWh): 2001 through 2015

<table>
<thead>
<tr>
<th>Year</th>
<th>Day Ahead</th>
<th>Real Time</th>
<th>Difference</th>
<th>Percent of Real Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
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<td>($0.37)</td>
<td>(1.1%)</td>
</tr>
<tr>
<td>2002</td>
<td>$28.46</td>
<td>$28.30</td>
<td>($0.16)</td>
<td>(0.6%)</td>
</tr>
<tr>
<td>2003</td>
<td>$38.73</td>
<td>$38.28</td>
<td>($0.45)</td>
<td>(1.2%)</td>
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<tr>
<td>2004</td>
<td>$41.43</td>
<td>$42.40</td>
<td>$0.97</td>
<td>2.3%</td>
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<tr>
<td>2005</td>
<td>$57.89</td>
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<td>0.3%</td>
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<tr>
<td>2006</td>
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<td>2.4%</td>
</tr>
<tr>
<td>2007</td>
<td>$54.67</td>
<td>$57.58</td>
<td>$2.90</td>
<td>5.3%</td>
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<tr>
<td>2008</td>
<td>$66.12</td>
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<td>$0.28</td>
<td>0.4%</td>
</tr>
<tr>
<td>2009</td>
<td>$37.00</td>
<td>$37.08</td>
<td>$0.08</td>
<td>0.2%</td>
</tr>
<tr>
<td>2010</td>
<td>$44.57</td>
<td>$44.83</td>
<td>$0.26</td>
<td>0.6%</td>
</tr>
<tr>
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<td>0.7%</td>
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<td>2014</td>
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<td>($0.93)</td>
<td>(1.9%)</td>
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<td>2015</td>
<td>$34.12</td>
<td>$33.39</td>
<td>($0.73)</td>
<td>(2.1%)</td>
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</table>
### Table 3-74 Day-ahead and real-time average LMP (Dollars per MWh): 2014 and 2015

<table>
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<th></th>
<th>2014</th>
<th>2015</th>
<th>Percent of Real Time</th>
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<th>2015</th>
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<tr>
<td></td>
<td>Day Ahead</td>
<td>Real Time</td>
<td>Difference</td>
<td>Day Ahead</td>
<td>Real Time</td>
<td>Difference</td>
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<td>Average</td>
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<td>$(0.93)</td>
<td>(1.9%)</td>
<td>$34.12</td>
<td>$33.39</td>
</tr>
<tr>
<td>Median</td>
<td>$38.10</td>
<td>$34.46</td>
<td>$(3.64)</td>
<td>(10.6%)</td>
<td>$29.09</td>
<td>$26.61</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>$51.88</td>
<td>$65.08</td>
<td>$13.20</td>
<td>20.3%</td>
<td>$22.59</td>
<td>$27.80</td>
</tr>
<tr>
<td>Peak average</td>
<td>$60.65</td>
<td>$59.12</td>
<td>$(1.54)</td>
<td>(2.6%)</td>
<td>$40.97</td>
<td>$39.44</td>
</tr>
<tr>
<td>Peak median</td>
<td>$44.55</td>
<td>$40.50</td>
<td>$(4.05)</td>
<td>(10.0%)</td>
<td>$33.69</td>
<td>$29.95</td>
</tr>
<tr>
<td>Peak standard deviation</td>
<td>$64.56</td>
<td>$81.78</td>
<td>$17.22</td>
<td>21.1%</td>
<td>$26.30</td>
<td>$30.23</td>
</tr>
<tr>
<td>Off peak average</td>
<td>$39.12</td>
<td>$38.72</td>
<td>$(0.41)</td>
<td>(1.1%)</td>
<td>$28.11</td>
<td>$28.08</td>
</tr>
<tr>
<td>Off peak median</td>
<td>$31.37</td>
<td>$29.39</td>
<td>$(1.98)</td>
<td>(6.7%)</td>
<td>$24.51</td>
<td>$23.62</td>
</tr>
<tr>
<td>Off peak standard deviation</td>
<td>$34.48</td>
<td>$43.64</td>
<td>$9.16</td>
<td>21.0%</td>
<td>$16.54</td>
<td>$24.28</td>
</tr>
</tbody>
</table>

83 The averages used are the annual average of the hourly average PJM prices for day-ahead and real-time.
Figure 3-41 PJM system hourly average LMP: 2015
Agenda

• LMP Components
• 5 Bus Model
• Shadow Prices
• Statistics
• LMP Simulation Demo
Questions?

PJM Client Management & Services
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Toll Free Telephone: (866) 400-8980
Website: www.pjm.com

The Member Community is PJM’s self-service portal for members to search for answers to their questions or to track and/or open cases with Client Management & Services.