Funding provided by U.S. Department of Energy Advanced Research Projects Agency–Energy (ARPA-E) under ARPA-E Award No. DE-AR001274 and Work Authorization No. 19/CJ000/07/08. The views expressed in the presentation do not necessarily represent the views of the DOE or the U.S. Government.
Outline

• Context
• Flexibility Options
• Key Observations and Next Steps
By 2050, almost 70% of electricity generation globally will come from solar photovoltaics and wind.


System operators and flexible resources must manage challenging energy imbalances.

Dataset: January 2017 to March 2019
Operational Flexibility for Managing Energy Imbalances

As lead time reduces, ...

- uncertainty with respect to energy imbalance decreases
- supply curves for Real-Time operational flexibility become steeper
Research Question

How will introducing a new *flexibility option* product in day-ahead ISO auction contribute to market efficiency and power system reliability?

Flexibility Options

Day-ahead  Hour-ahead  Minutes-ahead  Real-time operations

Endogenously consider cost of operational flexibility to manage imbalances
Outline

• Context

• Flexibility Options
  – Participants (Who?)
  – Product Definition (What?)
  – Formulation and Settlements (How?)

• Key Observations and Next Steps
Outline

• Context

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  – Formulation and Settlements (How?)

• Key Observations and Next Steps
Identify cost-effective hedging of energy imbalances with flexibility options.

BUYERS OF FLEXIBILITY OPTIONS

Uncertainty

Solar plants
Wind plants
Load-serving entities

SELLERS OF FLEXIBILITY OPTIONS

Flexibility

Power plants
Storage
Electric vehicles
Water heaters
Smart heating/cooling
Distributed energy resource aggregators
ISO Day-Ahead Markets

Uncertainty

BUYERS OF FLEXIBILITY OPTIONS

Solar plants
Wind plants
Load-serving entities

Identify cost-effective hedging of energy imbalances with flexibility options.

Set of percentiles ($\Omega_S$)
Probability of shortfall ($\Pi_{s,t}$)

SELLERS OF FLEXIBILITY OPTIONS

Power plants
Storage
Electric vehicles
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Smart heating/cooling
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Uncertainty

BUYERS OF FLEXIBILITY OPTIONS

- Solar plants
- Wind plants
- Load-serving entities

SELLERS OF FLEXIBILITY OPTIONS

- Power plants
- Storage
- Electric vehicles
- Water heaters
- Smart heating/cooling
- Distributed energy resource aggregators

ISO Day-Ahead Markets

Identify cost-effective hedging of energy imbalances with *flexibility options*.

- $P_{i,s,t}$: Generation or consumption
- $CAP_{i,r,t}^{1}$: Willingness to pay for hedging generation shortfalls.

Set of percentiles ($\Omega_{S}$)
Probability of shortfall ($\Pi_{s,t}$)
ISO Day-Ahead Markets

BUYERS OF FLEXIBILITY OPTIONS

Uncertainty

• $P_{i,s,t}$: Generation or consumption
• $\text{CAP}^{i}_{i,r,t}$: Willingness to pay for hedging generation shortfalls.

Identify cost-effective hedging of energy imbalances with flexibility options.

Set of percentiles ($\Omega_s$)
Probability of shortfall ($\Pi_{s,t}$)

SELLERS OF FLEXIBILITY OPTIONS

Flexibility

• $C^{\uparrow}_{i,r,t}$: strike price at which they would supply Real-Time energy.
• $C^{\downarrow}_{i,r,t}$: strike price at which they would buy Real-Time energy.
Outline

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A contract issuing rights to its purchaser to buy or sell energy *imbalance* during a market interval at a strike price.
A contract issuing rights to its purchaser to buy or sell energy **imbalance**s during a market interval at a strike price.

**Day-ahead energy award**

**Real-time physical availability**

- **Negative imbalance**
  - **Upward option**
    - “Call” option to purchase up to x MW at strike price.
    - Can be exercised only when imbalance is negative.

- **Positive imbalance**
  - **Downward option**
    - “Put” option to sell up to x MW at strike price.
    - Can be exercised only when imbalance is positive.
A contract issuing rights to its purchaser to buy or sell energy *imbalance* during a market interval at a strike price.

- **Day-ahead energy award**
- **Real-time physical availability**

### Negative Imbalance
- **Upward option**
  - “Call” option to purchase up to x MW at strike price.
  - Can be exercised only when imbalance is negative.

### Positive Imbalance
- **Downward option**
  - “Put” option to sell up to x MW at strike price.
  - Can be exercised only when imbalance is positive.

Option “tier” indicates the frequency at which the option can be exercised.
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Co-optimized within DA markets Formulation

Existing terms in objective function such as energy cost

\[
\min_{\Xi} \sum_{i \in \Omega_G' \cap \Omega_T} C_{i,t} \cdot p_{i,t} \cdot I_m + \cdots + \sum_{i \in \Omega_G' \cap \Omega_T} y_{i,s,t} \cdot y + \sum_{i \in \Omega_G' \cap \Omega_T} \left( \sum_{r \in \Omega_{R,t}} \left( \Pi_{r,t} \cdot C_{i,t} \cdot h_{i,r,t} \right) - \sum_{r \in \Omega_{R,t}} \left( \Pi_{r,t} \cdot C_{i,t} \cdot h_{i,r,t} \right) \right)
\]

Expected cost for flexibility deployment

Expected costs for fast start units

Expected “cost” of flexibility deficits

Preliminary and non-exhaustive
Co-optimized within DA markets Formulation

Existing terms in objective function such as energy cost

\[
\begin{align*}
\min \sum_{i \in \Omega G, t \in \Omega T} C_{i,t} \cdot p_{i,t} \cdot I_m & + \cdots + \sum_{i \in \Omega G, t \in \Omega T} y_{i,s,t} \cdot \gamma + \sum_{i \in \Omega G', t \in \Omega T} I_m \cdot \left( \sum_{r \in \Omega R_t} (\uparrow C A P_i, r, t \cdot \uparrow f_s a_i, r, t) \right) & \\
\end{align*}
\]

Expected cost for flexibility deployment

Expected costs for fast start units

Expected "cost" of flexibility deficits

Constraints related to the co-optimized flexibility auction

\[
\begin{align*}
\sum_{i \in \Omega G'} \uparrow h s_{i, r, t} &= \sum_{i \in \Omega G} \uparrow h d_{i, r, t} (\lambda_{r, t}^{F E L X \uparrow}) \\
\sum_{i \in \Omega G'} \downarrow h s_{i, r, t} &= \sum_{i \in \Omega G} \downarrow h d_{i, r, t} (\lambda_{r, t}^{F E L X \downarrow}) \\
\end{align*}
\]

Flexibility demand

\[
\begin{align*}
\sum_{r = \{1, \ldots, s-1\}} & \uparrow h d_{i, r, t} + \sum_{s \neq 1 \ldots |\Omega S_t|} \uparrow h d_{i, r, t} \leq y_{i,s,t} \\
\sum_{r = \{s, \ldots, |\Omega S_t|\}} & \uparrow h d_{i, r, t} + \uparrow f_s a_{i, r, t} \geq p_{i,t} - p_{i,s,t} \\
y_{i,s,t} \geq & \left| p_{i,t} - p_{i,s,t} \right|
\end{align*}
\]

Flexibility supply

\[
\begin{align*}
p_{i,t} + \sum_{r \in \Omega R_t} \uparrow h s_{i, r, t} & \leq p_{i,t}^{\max} \cdot u_{i,t} + \min(p_{i,t}^{\max}, R R_i) \cdot u f_{i,r=1,t} \\
p_{i,t} - \sum_{r \in \Omega R_t} \downarrow h s_{i, r, t} & \geq p_{i,t}^{\min} \cdot u_{i,t} \\
+ & \text{ramping constraints}
\end{align*}
\]
Two-Settlement System

Option pricing in Day-Ahead  
Option pay-off in Real-Time
Two-Settlement System

Option pricing in Day-Ahead

Buyer of upward flexibility option:

$$- (\lambda_{r,t}^{FLEX} - \uparrow \Pi_{r,t} \cdot \text{strike price}^*) \cdot \uparrow h_{i,r,t}$$

Seller of upward flexibility option:

$$(\lambda_{r,t}^{FLEX} - \uparrow \Pi_{r,t} \cdot C_{i,r,t}^\uparrow) \cdot \uparrow h_{s_i,r,t}$$

Option pay-off in Real-Time

* Strike price is MW-weighted average of $C_{i,r,t}^\uparrow$
Two-Settlement System

Day-ahead energy award \( p_i \)

Real-time physical availability \( RTP \)

**Option pricing in Day-Ahead**

Buyer of upward flexibility option:

\[-(\lambda_{r,t}^{FLEX} \uparrow - \uparrow \Pi_{r,t} \cdot \text{strike price}^*) \cdot \uparrow h_{i,r,t}\]

Seller of upward flexibility option:

\[(\lambda_{r,t}^{FLEX} \uparrow - \uparrow \Pi_{r,t} \cdot C_{i,r,t}) \cdot \uparrow h_{i,r,t}\]

**Option pay-off in Real-Time**

\[\max(0, \lambda_{t}^{RT-EN} - \text{strike price}^*) \cdot \max(0, \min(P_{i,r-1,t} + \uparrow h_{i,r,t}, p_i) - \max(RTP, P_{i,r-1,t}))\]

\[-\max(0, \lambda_{t}^{RT-EN} - C_{i,r,t}) \cdot \uparrow h_{i,r,t}\]

* Strike price is MW-weighted average of \( C_{i,r,t} \)
Outline

• Context

• Flexibility Options
  – Participants
  – Product Definition
  – Formulation
  – Settlements.

• Key Observations and Next Steps
Simple Example

**Flexibility buyers**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Probability</th>
<th>Renewable 1</th>
<th>Renewable 2</th>
<th>Aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>20%</td>
<td>67</td>
<td>64</td>
<td>131</td>
</tr>
<tr>
<td>S2</td>
<td>20%</td>
<td>74</td>
<td>67</td>
<td>141</td>
</tr>
<tr>
<td>S3</td>
<td>20%</td>
<td>83</td>
<td>72</td>
<td>155</td>
</tr>
<tr>
<td>S4</td>
<td>20%</td>
<td>90</td>
<td>75</td>
<td>165</td>
</tr>
<tr>
<td>S5</td>
<td>20%</td>
<td>95</td>
<td>77</td>
<td>172</td>
</tr>
</tbody>
</table>

Correlation of R1 & R2 ~1

**Flexibility suppliers**

<table>
<thead>
<tr>
<th>Variable cost ($/MWh)</th>
<th>Max capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST 1</td>
<td>20</td>
</tr>
<tr>
<td>CT 2</td>
<td>35</td>
</tr>
<tr>
<td>CT 3</td>
<td>50</td>
</tr>
<tr>
<td>CT 4</td>
<td>60</td>
</tr>
</tbody>
</table>

**Energy-only participants**

Load: 200 MW

**Strike price = Variable Cost**

**Ramp Rate = Capacity**

SIMPLE EXAMPLE presented at [https://cms.ferc.gov/media/w3-spyrou](https://cms.ferc.gov/media/w3-spyrou)
Standard deviation of day-ahead and real-time profits expected to decrease

Simple example presented at https://cms.ferc.gov/media/w3-spyrou
Simple Example [Modified: Unit Commitment]

### Load: 200 MW

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Probability</th>
<th>Renewable 1</th>
<th>Renewable 2</th>
<th>Aggregate</th>
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<td>95</td>
<td>77</td>
<td>172</td>
</tr>
</tbody>
</table>

Correlation of R1 to R2: ~1

### Energy-only participants

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Min capacity</th>
<th>Variable cost ($/MWh)</th>
<th>Max capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST1 (DA start)</td>
<td>44</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>ST2 (DA start)</td>
<td>25</td>
<td>22</td>
<td>50</td>
</tr>
<tr>
<td>CT 2</td>
<td>0</td>
<td>35</td>
<td>10</td>
</tr>
<tr>
<td>CT 3</td>
<td>0</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>CT 4</td>
<td>0</td>
<td>60</td>
<td>10</td>
</tr>
</tbody>
</table>

Strike price = Variable Cost
Ramp Rate = Capacity

**SIMPLE EXAMPLE** presented at [https://cms.ferc.gov/media/w3-spyrou](https://cms.ferc.gov/media/w3-spyrou)
Expected production cost and perfect forecast gap expected to decrease

$100$ $100$ $90$ $110$ $264$ $17$ $0$

SIMPLE EXAMPLE presented at https://cms.ferc.gov/media/w3-spyrou

Less steep RT supply curve for operational flexibility down (> 6 MW)
Next Steps

Simulations with ARPA-E PERFORM Texas system in FESTIV* to analyze the value of the introduction of flexibility options

- Comparison with other hedging instruments
- Analysis on risks for all parties involved

Performance analysis for distributed energy resource aggregators acting as flexibility suppliers

Thank you!

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