Aggregating Distributed Energy Resources: Efficiency and Market Power

Zuguang Gao\textsuperscript{1}, Khaled Alshehri\textsuperscript{2}, and John R. Birge\textsuperscript{1}

\textsuperscript{1}The University of Chicago
\textsuperscript{2}King Fahd University of Petroleum and Minerals
Overview

1. Introduction & Distributed Energy Resources (DERs)

2. Two Aggregation Models

3. Generators’ Market Power

4. Conclusion & Future Work
Introduction

• It is with little doubt that addressing the energy and environmental challenges, including climate change, is one of the top priorities of our time.

• Inflation Reduction Act of 2022

• Goal: decrease greenhouse gas emissions by 40% below 2005 levels in 2030, and eventually reach net zero by no later than 2050.
Distributed Energy Resources (DERs)

• DERs are small-scale power generation or storage technologies, which may be located at the end-consumers level in distribution power systems.

• Examples of DER: solar photovoltaics, electric storage, thermal storage, electric vehicles and their charging equipment.

• The rapid expansion of distributed energy resources (DERs) is one of the most significant changes to electricity systems around the world.
Increasing DER Adoption

Residential solar installations and forecast, 2018-2032

Source: Wood Mackenzie
DERs and Electricity Markets

- DERs can provide multiple services to the grid, including capacity, energy and ancillary services.
- DERs have too small supply capacities to directly participate in a wholesale electricity market.
- Need to include DER supply into the wholesale electricity market, but how?

1. Have a Distribution System Operator (DSO) acting as a market manager at the distribution level, and finding socially-optimal dispatch, similar to ISOs [Ntakou and Caramanis 2014, Huang et al. 2015, Manshadi and Khodayar 2016, Terra et al. 2017].
2. Have a fully-distributed electricity market designs, in which end-consumers can trade energy among themselves [Rahimi and Ipakchi 2012, Moret and Pinson 2018].
3. Have an aggregating company whose role is to collect energy from DER owners, and participate in the wholesale market as a producer of electricity [This work].
DER aggregation via profit-seeking intermediaries has been adopted by California ISO and New York ISO [G undlach and Webb 2018, Lavillotti 2018].

FERC Order No. 2222 paved the way for aggregators to bid in the wholesale market.

Research Question
In the presence of a profit-seeking and a monopolistic aggregator, is there an aggregation model that can attain a socially optimal (efficient) market outcome?

Our answer: two efficient aggregation models.

- Unregulated aggregator, differential two-part pricing
- Regulated aggregator, uniform two-part pricing
**Direct Participation Model**

**Wholesale Market**  
*(social welfare maximization)*

- **Prices and quantities**
- **Offers/Bids**

### Prosumers

- **Prosumer’s problem**
  \[
  \max_{z_i^k} \pi_i^k(z_i^k) := \lambda^k z_i^k + u_i^k(C_i^k - z_i^k)
  \]
  s.t. \( C_i^k - Z \leq z_i^k \leq C_i^k \).

- **Generator’s problem**
  \[
  \max_{y_j^k} \hat{\pi}_j^k(y_j^k) := \lambda^k y_j^k - c_j^k(y_j^k).
  \]
  \( y_j^k \in [\underline{y}_j^k, \overline{y}_j^k] \)

- **The economic dispatch problem**
  \[
  \max \sum_{k \in [n]} \left( \sum_{i \in [n_k]} u_i^k(C_i^k - z_i^k) - \sum_{j \in [N_k]} c_j^k(y_j^k) \right)
  \]
  subject to supply demand balance  
  network constraints.
Unregulated Aggregation Model

- Prosumer sees \((P^k_i, p^k_i)\) announced by the aggregator.

\[
\pi^k_i(x^k_i, d^k_i) := \begin{cases} 
 p^k_i x^k_i - P^k_i + u^k_i (d^k_i + C^k_i - x^k_i) - \lambda^k d^k_i, & \text{if } x^k_i > 0, \\
 u^k_i (d^k_i + C^k_i) - \lambda^k d^k_i, & \text{if } x^k_i = 0.
\end{cases}
\]

Prosumer’s problem

\[
\max_{x^k_i \in [0, C^k_i], d^k_i \in [0, Z - C^k_i + x^k_i]} \pi^k_i(x^k_i, d^k_i).
\]

- Aggregator’s problem

\[
\max_{P \geq 0, p \geq 0} \sum_{i \in [n_k]} \sum_{k \in [n]} \left[ P^k_i \mathbb{1} \left\{ x^k_i (P^k_i, p^k_i) > 0 \right\} + (\lambda^k - p^k_i) x^k_i (P^k_i, p^k_i) \right].
\]
Let $z_i^k$ be such that $\frac{\partial u_i^k(z)}{\partial z} \bigg|_{z=z_i^k} = \lambda^k$.

### Competitive Equilibrium

There exists a competitive equilibrium with

- $p_i^{k*} = \lambda^k$,
- $P_i^{k*} = \left[ \lambda^k (C_i^k - z_i^k) + u_i^k (z_i^k) - u_i^k (C_i^k) \right]^+$
- $d_i^{k*} = [z_i^k - C_i^k]^+$, $x_i^{k*} = [C_i^k - z_i^k]^+$
- $\lambda^k$ is the same as in the direct participation model.

### Efficiency Result

Unregulated aggregation model achieves the same social welfare as the direct participation model, i.e., there is no loss of market efficiency from the aggregation.
Unregulated Aggregation Model - Example

Figure: **Left:** Efficient aggregation vs. no DER integration. **Middle:** Comparison between the two extremes and the one-part pricing model. **Right:** Quantification of the efficiency loss for the one-part pricing model.
Regulated Aggregation Model

- Regulated aggregator is required to set the prices as $p^k = \lambda^k$ and
  $$P^k = \min_{i\in[n_k]|x_i^k > 0} u_i^k(z_i^k) + \lambda^k(C_i^k - z_i^k) - u_i^k(C_i^k).$$
- Full market efficiency.
- Aggregator’s profit could be small (or even zero).

- An extra charge $F_i^k$ is imposed on prosumer $i$, to be forwarded to the aggregator.
- $F_i^k$ is a linear function on the demand of the prosumer when there is no DER aggregation.
- Competitive equilibrium: market price is $\lambda^k$, prosumers’ optimal decisions unchanged.
- Aggregator’s profit at location $k$ is $\Pi^k = \sum_{i\in[n_k]|x_i^k > 0} P^k + \sum_{i\in[n_k]} F_i^k$. 

Wholesale Market 
(social welfare maximization)

Retail Aggregator 
(regulated)

Prosumers

Prices and quantities

Two-price offers

Supply offers

DER capacities

Prices and quantities

Two-price offers

Supply offers

DER capacities
Regulated Aggregation Model - Results

Efficiency Result

Regulated aggregation model achieves the same social welfare as the direct participation model, i.e., there is no loss of market efficiency from the aggregation.

Three types of prosumers:

**Type I.** Prosumers with
\[ d_i^k \geq \hat{d}_i^k > 0, \quad \text{i.e.,} \quad \frac{\partial u_i^k}{\partial z} \bigg|_{z=C_i^k} \hat{\lambda}^k \geq \lambda_i^k. \]

**Type II.** Prosumers with
\[ d_i^k > \hat{d}_i^k = 0, \quad \text{i.e.,} \quad \hat{\lambda}^k \geq \frac{\partial u_i^k}{\partial z} \bigg|_{z=C_i^k} > \lambda_i^k. \]

**Type III.** Prosumers with
\[ \hat{d}_i^k = d_i^k = 0, \quad \text{i.e.,} \quad \hat{\lambda}^k \geq \lambda_i^k \geq \lambda_i^k. \]

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<tbody>
<tr>
<td>Type I</td>
<td>Low</td>
<td>Highest</td>
<td>High</td>
<td>always buying</td>
</tr>
<tr>
<td>Type II</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>buying after aggregation</td>
</tr>
<tr>
<td>Type III</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>selling after aggregation</td>
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Figure: **Left:** TYPE I prosumer is always buying and achieves the maximum surplus for the unregulated model. **Middle:** TYPE II prosumer achieves the maximum surplus for both the unregulated and regulated models. **Right:** TYPE III prosumer is always selling and achieves the maximum surplus in the regulated model.
Generators’ Market Power

- Previous models: assumed truthful bidding of generators.
- Now, suppose generators can bid strategically (non-truthful).

Research Question
When DERs are aggregated, can the market power of conventional power generators be mitigated? If yes, to what extent?
Generators’ Market Power

Four different models:

<table>
<thead>
<tr>
<th>Generators bidding</th>
<th>Full prosumer participation</th>
<th>No prosumer participation</th>
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<tr>
<td>truthfully</td>
<td>$\mathcal{W}^T$, $\lambda^T$</td>
<td>$\mathcal{W}^{TN}$, $\lambda^{TN}$</td>
</tr>
<tr>
<td>strategically</td>
<td>$\mathcal{W}^S$, $\lambda^S$</td>
<td>$\mathcal{W}^{SN}$, $\lambda^{SN}$</td>
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Reduction on market power

The following inequalities hold:

$$\lambda^{SN} > \lambda^S > \lambda^T = \lambda^{TN},$$

$$\mathcal{W}^T \geq \mathcal{W}^{TN}, \quad \mathcal{W}^T \geq \mathcal{W}^S,$$

$$\mathcal{W}^S \geq \mathcal{W}^{SN}, \quad \mathcal{W}^{TN} \geq \mathcal{W}^{SN},$$

$$\mathcal{W}^{TN} - \mathcal{W}^{SN} \geq \mathcal{W}^T - \mathcal{W}^S.$$
Generators’ Market Power - Illustration

Figure: **Left:** Social welfare for each market setup vs. $N$. **Middle:** Quantification of market power in terms of social welfare loss. **Right:** Price for each market setup vs. $N$. 
Conclusion & Future Work

Summary:

• It is possible to achieve full market efficiency in the presence of monopolistic aggregator.
• Two aggregation models: unregulated/regulated aggregator, differential/uniform pricing.
• DER aggregation reduces the market power of conventional generators.

Future work:

• How efficient aggregation models would impact investments and rebates for the installations of DER capacities? [Hu et al. 2015, Kök et al. 2018, Aflaki and Netessine 2017, Babich et al. 2020]
• Study the affect of competition among aggregators under different pricing policies and also their strategic bidding in networked wholesale markets. [Anupindi and Jiang 2008, Ruhi et al. 2018, Bimpikis et al. 2019, Nguyen and Kannan 2021, Aravena et al. 2021]
Thank you!

Questions? zuguang.gao@chicagobooth.edu