Competitive DER Aggregation for Participation in Wholesale Markets

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Abstract

The problem of the large-scale aggregation of behind-the-meter demand and generation resources by a distributed-energy-resource aggregator (DERA) is considered. As a wholesale market participant, a DERA maximizes its profit while providing competitive services to its customers with higher consumer/prosumer surpluses than those offered by the distribution utilities or community choice aggregations. A constrained profit maximization program for aggregating behind-the-meter generation and consumption resources is formulated, from which payment functions for the behind-the-meter consumptions and generations are derived. Also obtained are DERA's bid and offer curves for its participation in the wholesale energy market.

Keywords: distributed energy resources and aggregation, behind-the-meter distributed generation, demand-side management, net energy metering, competitive wholesale market.

1. Introduction

The landmark ruling of the Federal Energy Regulatory Commission (FERC) order 2222 aims to remove barriers to the direct participation of distributed-energy-resource aggregators (DERAs) in wholesale electricity markets operated by Regional Transmission Organizations and Independent System Operators (RTO/ISO) (FERC, 2020). By leveraging technological advances in metering and telemetry infrastructure, data-driven energy management, and machine learning technologies, a profit-maximizing DERA can aggregate at scale the growing presence of small-sized generation and demand resources in its participation in the wholesale energy, ancillary, and capacity markets.

Since the release of FERC Order 2222, significant concerns have been raised about whether DERAs can be profitable from wholesale market participation (Borenstein et al., 2021). In particular, given that behind-the-meter (BTM) prosumers enjoy significant bill savings under various net energy metering (NEM) tariffs, attracting customers away from their incumbent utilities or community choice aggregators (CCAs) is a significant challenge (Birk et al., 2017; Nelson, 2021; Gundlach and Webb, 2018).

This paper focuses on the *competitive DER aggregation* of a profit-seeking DERA in the wholesale energy market. By competitive DER aggregation, we mean that the DERA must offer its customers higher consumer/prosumer surpluses than those from their incumbent service providers.

The challenge of achieving profitable competitive DER aggregation is twofold. First, the DERA must extract more surpluses from distributed generation and demand resources than individual customers can under the NEM tariff. Second, a DERA must maximize its profit from its wholesale market participation, gaining surpluses by offering the wholesale market its aggregated distributed generations and flexible demand resources. To this end, the DERA, as a wholesale market participant, must derive its profit-maximizing offers and bids from its competitive DER aggregation strategy.

1.1. Related work

There is growing literature on the DER aggregation and participation models that broadly fall into two categories. One is through a retail market design operated by a distribution system operator (DSO) or an aggregation platform (Haider et al., 2021; Manshadi and Khodayar, 2015; Chen and Zhao, 2022). The second category of aggregation, a focus of the FERC order 2222, is by independent (possibly profit-maximizing) DERA, which aggregates both generation and flexible

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demand resources in the retail market, bypassing the regulated distribution utility and DSO in participating in the wholesale energy market (Gao et al., 2021; Alshehri et al., 2020). The DER aggregation considered in this paper belongs to the second category.

While competitive DER aggregation has not been articulated previously, the work of Gao et al. (2021) is perhaps the first to imply such a formulation. In particular, the Gao-Alshehri-Birge (GAB) approach guarantees its customers to achieve a surplus equal to that achievable by their direct participation in the competitive wholesale market as a consumer. In other words, the GAB approach is competitive with the most economically efficient consumer participation model.

The approach proposed by Gao et al. (2021) follows an earlier work of Alshehri et al. (2020) where a Stackelberg game-theoretic model is used. Both approaches assume that the DERA elicits prosumer participation with a (one-part or two-part) price, and the prosumer responds with its quantity to supply. The DERA optimizes the price offered to its customers based on anticipated wholesale market price, and the DERA submits a quantity bid to the wholesale energy market. The DER aggregation model presented here is significantly different. We assume that the DERA schedules directly the customer consumption while guaranteeing a competitive advantage over alternative aggregation models. The DERA submits an offer/bid curve (rather than a quantity) to the wholesale energy market without having to anticipate the market clearing price. Only the expected total BTM generation is needed in the DERA's bid in the wholesale market.

Another set of relevant works is based on the notion of CCA, which offers aggregation services to its customers (Chakraborty et al., 2018; Kalathil et al., 2017; Han et al., 2018). Without emphasizing the profit-maximization of the aggregator, these techniques do not pursue a bi-level optimized solution with its customers on the one side and the wholesale energy market on the other. The approach particularly relevant to the notion of competitive aggregation comes from Chakraborty et al. (2018). They proposed an aggregation approach that guarantees a competitive advantage over the utility's NEM tariff for those aggregated customers.

For competitive aggregation, it is necessary to characterize achievable surpluses by alternative aggregation models, especially for the broadly adopted NEM-based pricing schemes. To this end, we rely on recent works from Alahmed and Tong (2022b,a) on the optimal prosumer decision under NEM-X tariffs.

1.2. Summary of results and limitations

To our best knowledge, this paper develops the first profit-maximizing competitive DER aggregation solution for a DERA to participate in the wholesale electricity market. Specifically, we propose a DER aggregation approach based on a constrained optimization that maximizes DERA surplus subject to its customers achieving surpluses competitive to various versions of utility/CCA-offered NEM rates. We then derive profit-maximizing bids and offers in the wholesale electricity market under the price-taking assumption. Finally, we present a set of numerical results, comparing the DERA surplus of the proposed competitive aggregation solution with those of various alternatives. We also compare surpluses of prosumers under different retail market participation models, including regulated utility, CCA, and DERAs.

In presenting the overall aggregation architecture and aggregation solution, we have ignored some of the details in a practical implementation. First, we ignore losses in distribution systems, assuming the customers' net generations/demands are aggregated without loss at the interconnecting point of the transmission system. In practice, some efficiency parameters may be incorporated, similar to the case of storage participation in the wholesale market (CAISO, 2020). Second, we assume that the DERA has a contract with the DSO for its use of the DSO's network in the form of a fixed cost, which is passed to the customers as connection or delivery charges. Such an assumption is consistent with the existing consumer aggregation model in many of the US markets (NYISO, 2020; ISO-NE, 2021). We, therefore, do not account for this part of the aggregation cost and DERA's own operation cost. Third, under FERC order 2222, DSO may have the right to reject cleared bids and offers of a DERA in the wholesale market for reliability reasons (FERC, 2020). Our model does not capture the impact of such interventions.

1.3. Notations and symbols

A list of major designated symbols is shown in Table 1. The notations used here are standard. When necessary, we use boldface letter to indicate column vector as in $\boldsymbol{x} = (x_1, \cdots, x_n)$. In particular, $\mathbf{1}$ and $\mathbf{0}$ are column vectors of all ones and zeros, respectively. For a vector $\boldsymbol{x}$, $\boldsymbol{x}^\top$ is the transpose of $\boldsymbol{x}$. For a multivariate function f of $\boldsymbol{x}$, we use interchangeably $f(\boldsymbol{x})$ and $f(x_1, \cdots, x_n)$. For vectors $\boldsymbol{x}$ and $\boldsymbol{y}$, $\boldsymbol{x} \preceq \boldsymbol{y}$ is the element-wise inequality representing $x_i \leq y_i, \forall i$. $[\boldsymbol{x}]^+$ and $[\boldsymbol{x}]^-$ are respectively the positive and negative parts of $\boldsymbol{x}$, *i.e.*, $[x_i]^+ = \max\{0, x_i\}$, $[x_i]^- = -\min\{0, x_i\}$ for all i, and $\boldsymbol{x} = [\boldsymbol{x}]^+ - [\boldsymbol{x}]^-$.

Table 1. Major symbols (alphabetically ordered).

$\boldsymbol{d}, \boldsymbol{D}$:	consumption bundle of a single customer and all customers.
$\overline{\boldsymbol{d}}, \underline{\boldsymbol{d}}$:	upper and lower limits of consumption bundles.
$\overline{D}, \underline{D}$:	upper and lower limits of the total consumption.
d^+, d^-:	total consumption in net-consumption and net-production zones.
$d_{\text{NEM-a}}, d_{\text{NEM-p}}$:	total consumption of active and passive prosumers.
g, G:	BTM single and aggregated DG.
K:	total number of devices.
$\mathcal{K}$:	competitive scheme's surplus level.
N:	total number of prosumers.
ω:	payment function under DERA.
ζ:	markup percent over the competing prosumer surplus.
P^{π}_{NEM}:	prosumer energy bill under tariff π.
π^+, π^-, π^0:	buy rate, export rate and fixed charges.
π_{LMP}:	wholesale locational marginal price.
Q:	aggregated net production of DERA.
$S^{\pi}_{\text{NEM}}, S_{\text{DERA}}$:	single prosumer and DERA surpluses.
$S^{\pi}_{\text{NEM-a}}, S^{\pi}_{\text{NEM-p}}$:	active and passive prosumers surplus under tariff π.
$\mathscr{S}(\cdot)$:	aggregated supply function.
$U(\cdot)$:	utility function of customers.
$V(\cdot)$:	marginal utility function.
z:	prosumer's net-consumption.

2. Competitive DER aggregation

We present DERA models, NEM-based competitive benchmarks, and optimized DER aggregation.

2.1. DERA interaction with DSO & RTO/ISO

We consider a generic interaction model among DERA, DSO, and RTO/ISO shown in Fig. 1, where a DERA uses DSO's physical infrastructure to deliver power to and from its customers. It is essential to delineate the financial and physical interactions between DERA and its customers, DERA and RTO/ISO, and DERA and DSO.

DERA and its customers. We assume a single-bill model for all DERA customers, where each customer

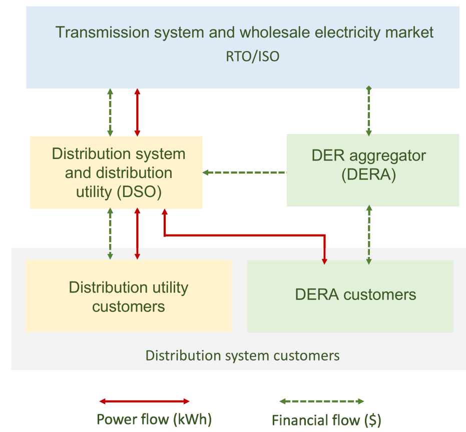

Figure 1. DERA model's physical and financial interactions.

is billed for its net consumption by the DERA. The billing period is consistent with that of the regulated utility. The DERA installs an energy management system (EMS) with sensors that measure distributed generation at the customer site. The DERA can control major customer consumptions such as heating and air conditioning, water-heater, EV charging, and other controllable energy devices such as battery storage. From its sensors and the reading of its customer's net energy meter, the DERA can account for actual generation and consumption by the customer.

DERA and DSO The DERA uses DSO's network and pays DSO for its usage as a fixed cost, which is passed to its customer as a connection charge similar to existing retail tariffs and CCA prices. The DSO measures the net consumption of DERA's customers and shares the readings with DERA. No additional metering is necessary. The DSO is required to pass the aggregated net consumption to the transmission interconnect. This ensures the strict separation of generations and consumptions from DERA and DSO, thus avoiding double counting.

DERA and RTO/ISO The DERA submits its offers and bids to the day-ahead or real-time wholesale energy markets (see Sec. 3). The ISO clears the offers/bids and settles payments with the DERA. In the real-time market, the DERA implements its control through its EMSs at the customer sites.

2.2. NEM benchmarks

A prosumer in a distribution system can choose to enroll in a NEM X retail program offered by her utility, a community choice aggregation (CCA), or a DERA for energy-providing services. A summary of several existing models for the participation of prosumers in utility, CCA, and DERA schemes is presented in Sec. 4

In this section, we consider the benchmark performance of a regulated utility offering the NEM tariff. To this end, we leverage the results of Alahmed and Tong (2022a,b) and present closed-form characterizations of consumer/prosumer surpluses.

Consider a prosumer with K energy-consuming devices. Let the K-consumption bundle of this prosumer be $\boldsymbol{d} \in \mathbb{R}_+^K$. We assume that the utility function $U(\cdot)$ is concave, nonnegative, monotonically increasing, continuously differentiable, and additive across the K devices. Let $V_k(x) := \frac{d}{dx}U_k(x)$ be the marginal utility of consuming x in device k.

The prosumer's net consumption is

$$z = \mathbf{1}^\intercal \boldsymbol{d} - g, \tag{1}$$

where $g \in [0, \infty)$ is the BTM renewable distributed generation (DG). The prosumer is a producer if $z < 0$ and a consumer if $z \geq 0$.

In evaluating the benchmark prosumer surplus under a regulated utility, we assume that the prosumer maximizes its surplus under the utility's NEM X tariff with parameter $\pi = (\pi^+, \pi^-, \pi^0)$, where π^+ is the retail (consumption) rate, π^- the sell (production) rate, and π^0 the fixed connection charge. Under such a tariff, the prosumer's energy bill $P^\pi_{\text{NEM}}(z)$ (Alahmed and Tong, 2022b) for net consumption z is given by

$$P^\pi_{\text{NEM}}(z) = \pi^+[z]^+ - \pi^-[z]^- + \pi^0, \tag{2}$$

where $[z]^+$ and $[z]^-$ are absolute values for positive and negative parts of z, respectively. The prosumer surplus under NEM with parameter π is therefore

$$S^\pi_{\text{NEM}}(\boldsymbol{d}) := U(\boldsymbol{d}) - P^\pi_{\text{NEM}}(z). \tag{3}$$

For an *active prosumer* whose consumption is a function of the available DG output g, the optimal consumption $\boldsymbol{d}_{\text{NEM-a}}$ and prosumer surplus $S_{\text{NEM-a}}(g)$ can also be obtained by

$$\boldsymbol{d}_{\text{NEM-a}} = \arg \max_{\underline{\boldsymbol{d}} \preceq \boldsymbol{d} \preceq \bar{\boldsymbol{d}}} U(\boldsymbol{d}) - P^\pi_{\text{NEM}}(\mathbf{1}^\intercal \boldsymbol{d} - g). \tag{4}$$

Therefore, the total consumption $d_{\text{NEM-a}} = \mathbf{1}^\intercal \boldsymbol{d}_{\text{NEM-a}}$ and the surplus $S_{\text{NEM-a}}(g)$ of *active prosumers* are given as Alahmed and Tong (2022b) by the following equations

$$S_{\text{NEM-a}}(g) = U(\boldsymbol{d}_{\text{NEM-a}}) - P^\pi_{\text{NEM}}(\mathbf{1}^\intercal \boldsymbol{d}_{\text{NEM-a}} - g) \tag{5}$$

$$= \begin{cases} U(\boldsymbol{d}^-) - \pi^-(\mathbf{1}^\intercal \boldsymbol{d}^- - g) - \pi^0, & g \geq \mathbf{1}^\intercal \boldsymbol{d}^- \\ U(\boldsymbol{d}^+) - \pi^+(\mathbf{1}^\intercal \boldsymbol{d}^+ - g) - \pi^0, & g \leq \mathbf{1}^\intercal \boldsymbol{d}^+ \\ U(g) - \pi^0, & \text{otherwise} \end{cases},$$

$$d_{\text{NEM-a}} = \max\{\mathbf{1}^\intercal \boldsymbol{d}^+, \min\{g, \mathbf{1}^\intercal \boldsymbol{d}^-\}\}, \tag{6}$$

where $d_k^+ := \max\{\underline{d}_k, \min\{V_k^{-1}(\pi^+), \bar{d}_k\}\}$, and $d_k^- := \max\{\underline{d}_k, \min\{V_k^{-1}(\pi^-), \bar{d}_k\}\} \geq d_k^+$. The prosumer is in the net-consumption zone if $g \geq \mathbf{1}^\intercal \boldsymbol{d}^-$, and the net-production zones if $g \leq \mathbf{1}^\intercal \boldsymbol{d}^+$.

We call a prosumer passive if the consumption schedule is independent of the DG output, i.e., all generation is used for bill reductions. The optimal consumption of such a *passive prosumer* under the NEM X tariff is given by Alahmed and Tong (2022a) as

$$\boldsymbol{d}_{\text{NEM-p}} = \arg \max_{\underline{\boldsymbol{d}} \preceq \boldsymbol{d} \preceq \bar{\boldsymbol{d}}} U(\boldsymbol{d}) - \pi^+(\mathbf{1}^\intercal \boldsymbol{d} - g). \tag{7}$$

The total consumption $d_{\text{NEM-p}} = \mathbf{1}^\intercal \boldsymbol{d}_{\text{NEM-p}}$ and the surplus $S_{\text{NEM-p}}(g)$ of a *passive prosumer* is given by

$$S_{\text{NEM-p}}(g) = U(\boldsymbol{d}_{\text{NEM-p}}) - P^\pi_{\text{NEM}}(\mathbf{1}^\intercal \boldsymbol{d}_{\text{NEM-p}} - g) \tag{8}$$

$$= \begin{cases} U(\boldsymbol{d}^+) - \pi^-(\mathbf{1}^\intercal \boldsymbol{d}^+ - g) - \pi^0, & g \geq \mathbf{1}^\intercal \boldsymbol{d}^+ \\ U(\boldsymbol{d}^+) - \pi^+(\mathbf{1}^\intercal \boldsymbol{d}^+ - g) - \pi^0, & g < \mathbf{1}^\intercal \boldsymbol{d}^+ \end{cases}$$

$$d_{\text{NEM-p}} = \mathbf{1}^\intercal \boldsymbol{d}^+. \tag{9}$$

Both passive and active prosumer classes can be considered in competitive DER aggregation. In practice, because active prosumer decision requires installing special DG measurement devices and sophisticated control, most prosumers are passive[1].

2.3. Optimal Competitive DER Aggregation

We now consider the optimal DER aggregation of a DERA that maximizes its profit via wholesale market participation. The retail pricing rule, designed by DERA to charge the aggregated customers, follows regulation restrictions applied to *competitive retailers*. In New York state, for example, regulated utility companies are prohibited to be profit-making under the regulatory restrictions, and the *default retail price* is set by the regulators. Pricing rules from other *competitive retailers*

[1]Britain establishes a database for passive customers and encourages the participation of passive customers in the electricity market (Ros et al., 2018).

should be provided to customers so that they can compare with the *default retail price* and choose the one that benefits them most (Ros et al., 2018).

Consider a DERA aggregating N prosumers via centrally scheduling the consumptions. In deriving the offers/bids in the wholesale market, the DERA needs to obtain optimal aggregated production/consumption as functions of the wholesale locational marginal price (LMP) π_{LMP} at the location of its interconnection with the transmission system. In particular, the DERA solves for the consumption bundle of all customers and their payment functions

$$\boldsymbol{D} = (\boldsymbol{d}_n, n = 1, \cdots, N),$$

$$\boldsymbol{\omega}^*(\boldsymbol{D}, \boldsymbol{g}) = (\omega_n^*(\boldsymbol{d}_n, g_n), n = 1, \cdots, N),$$

from the following optimization

$$\begin{array}{rl} \max\limits_{\boldsymbol{\omega}, \boldsymbol{D}} & \sum_{n=1}^N (\omega_n - \pi_{\text{LMP}}(\mathbf{1}^\intercal \boldsymbol{d}_n - g_n)) \\ \text{subject to} & \text{for all } 1 \le n \le N \\ \lambda_n : & \mathcal{K}_n(g_n) \le U_n(\boldsymbol{d}_n) - \omega_n, \\ (\underline{\boldsymbol{\mu}}_n, \bar{\boldsymbol{\mu}}_n) : & \underline{\boldsymbol{d}}_n \preceq \boldsymbol{d}_n \preceq \bar{\boldsymbol{d}}_n, \end{array} \tag{10}$$

where the first constraint, referred to as *$\mathcal{K}$-competitive constraint* ensures that the prosumer surplus under DERA is ζ-percent markup over the competing prosumer surplus with $\zeta \ge 0$. For example, to obtain competitive aggregation over the utility's NEM-based aggregation scheme for *passive prosumers*, we have $\mathcal{K}_n(g_n) = (1 + \frac{\zeta}{100})S_{\text{NEM-p}}(g_n)$ with $S_{\text{NEM-p}}(g_n)$ computed from (8), which guarantees that the prosumer surplus is no less than that ζ percent higher surplus under NEM X. Similarly with (5), competitiveness over *active prosumers* can be preserved by setting the surplus level $\mathcal{K}_n(g_n) = (1 + \frac{\zeta}{100})S_{\text{NEM-a}}(g_n)$.

Note that the solution of the above optimization, in general, implies that the optimal consumption $\boldsymbol{d}_n^*$ is a function of the local DG g_n, which would complicate the use of the above optimization as a way to construct offers/bids in the wholesale electricity market because offers/bids must be submitted before the realization of BTM DG. Fortunately, such a concern is unwarranted as the optimal consumption is independent of g_n.

Theorem 1 (Optimal DERA scheduling and payment)**.** *Compute (10) with the given wholesale market LMP π_{LMP}, the optimal consumption bundle $\boldsymbol{d}_n^* = (d_{kn})$ of prosumer n and its payment $\omega_n^*(\boldsymbol{d}_n^*, g_n)$ are given, respectively, by*

$$d_{kn}^* = \max\{\underline{d}_k, \min\{V_{kn}^{-1}(\pi_{LMP}), \bar{d}_k\}\} \tag{11}$$

$$\omega_n^*(\boldsymbol{d}_n^*, g_n) = U_n(\boldsymbol{d}_n^*) - \mathcal{K}_n(g_n), \tag{12}$$

where $\underline{d}_{kn}, \bar{d}_{kn}$ are repectively the lower and upper consumption limits for the k-th device of prosumer n.

The proof follows directly the KKT conditions of (10). The DERA's surplus from the wholesale electricity markets is given by

$$S_{\text{DERA}} := \sum_{n=1}^N (\omega_n^* - \pi_{\text{LMP}}(\mathbf{1}^\intercal \boldsymbol{d}_n^* - g_n)). \tag{13}$$

Note that the optimal consumption for the k-th device of prosumer n, i.e. d_{kn}^*, are only a function of the wholesale market LMP, π_{LMP}, independent of the local BTM DG g_n, and the payment, ω_n. The optimal DERA payment function ω_n^*, naturally, depends on both the consumption and BTM DG. The significance of such dependencies is that, once the wholesale market LMP is realized, the scheduled consumption is optimal, unlike cases from Gao et al. (2021) and Alshehri et al. (2020), where the optimally scheduled consumption depends on the BTM DG forecasts and the anticipated LMP.

Also significant is that the solution given in Theorem 1 provides directly the supply and demand curves that the DERA submits to the wholesale energy market. Note that $\boldsymbol{d}_n^*$ is the same as the optimal consumption of the prosumer n when it directly participates in the wholesale energy market with

$$\max_{\boldsymbol{d}_n} \; U_n(\boldsymbol{d}) - \pi_{\text{LMP}}(\mathbf{1}^\intercal \boldsymbol{d}_n - g_n), \tag{14}$$

which is identical to the DER aggregation scheme proposed by Gao et al. (2021). This means that the DERA participation in the wholesale energy market results in overall market efficiency.

3. DERA in the wholesale market

Having obtained the profit-maximizing DER aggregation, we now turn our attention to DERA's participation in the wholesale energy market. Here we assume that the DERA is a price-taker in a competitive market.

DERA can participate in the wholesale energy market as a virtual storage facility (ISO-NE, 2021), which allows DERA to inject power into or withdraw power from the wholesale energy market. This section analyzes the optimal bidding strategies in the wholesale energy market as a price taker in a competitive market setting.

One form of the bid from a DERA is the quantity bid, where the DERA submits a quantity to buy/sell power to meet the aggregated demand/supply. Constructing such offers/bids typically requires optimization based on anticipated market clearing price and DG. Stochastic optimizations can be used to mitigate uncertainties in clearing prices and renewable generation. The market-clearing LMP is used to settle the supply/demand[2]. See examples from Gao et al. (2021) and Alshehri et al. (2020) for constructing such bids in DER aggregation.

We focus on the commonly used price-quantity bids that express the DERA's willingness to buy/sell its aggregated resources. In a competitive market, such a price-quantity curve is in the form of the marginal cost of production or marginal benefit of consumption. For the competitive DER aggregation, we develop such offers/bids from the DERA's constrained optimization displayed in (10).

As shown in Sec.2.3, the DERA considered in this paper optimizes its DER resources to buy or sell in the wholesale energy market. To this end, the DERA submits a bid curve in the market auction to buy or sell its aggregated resources. Such a bid curve—herein referred to as supply function[3], can be constructed as follows.

Let Q be the aggregated quantity to sell (when $Q > 0$) or buy (when $Q < 0$) for the DERA and π be the wholesale energy market clearing price (LMP). Let $G = \sum_{n=1}^{N} g_n$ be the aggregated distributed generation. It is known that in a competitive market, a price-taking DERA participant bids truthfully with its aggregated supply function $\mathscr{S}(\cdot)$ given by Theorem 1 in (11):

$$\mathscr{S}(\pi) = G - \max\{\underline{D}, \min\{f(\pi), \bar{D}\}\}, \qquad (15)$$

where $\underline{D} =: \sum_{n=1}^{N} \mathbf{1}^\intercal \underline{\boldsymbol{d}}_n, \bar{D} := \sum_{n=1}^{N} \mathbf{1}^\intercal \bar{\boldsymbol{d}}_n$, and $f(\pi) := \sum_{n=1}^{N} \mathbf{1}^\intercal \boldsymbol{d}_n^*$. Additionally, we have $Q = \mathscr{S}(\pi)$ by definition. Note that the inverse supply function is the marginal cost of DERA's aggregation. And to create a supply function in (15), the DERA only needs to forecast the aggregated renewable generations.

4. Participation model of prosumers

A prosumer participating in the retail market can choose to enroll with the NEM X retail program offered by the utility or enroll with the DERA participation scheme. In this context, a summary of several existing models for the participation of *passive prosumers* in the regulated utility, the CCA and DERA schemes are respectively presented[4].

[2]LMP is denoted by π in this section for simplicity

[3]Here we generalize the terminology of supply function to include both purchase and sell of electricity.

[4]For simplicity, $U_i(d_i^{\text{NEM-p}})$ in this section represents the total utility over all devices for passive prosumer i, i.e. $\sum_k U_{ik}(d_{ik}^+)$.

4.1. NEM X

Consider N prosumers under NEM X. Let γ be the fraction of producers indexed by i with $d_i^{\text{NEM-p}} - g_i \leq 0, \forall i \in \{1, ..., \gamma N\}$, and $1 - \gamma$ be the fraction of consumers indexed by j with $d_j^{\text{NEM-p}} - g_j \geq 0, \forall j \in \{\gamma N + 1, ..., N\}$. The surplus of the utility company is

$$\begin{aligned} S^{\text{NEM-u}}(\pi^+, \pi^-) \; = \; & \textstyle\sum_{i,j} \Big(\pi^0 + (\pi^- - \pi_{\text{LMP}}) z_i^{\text{NEM-p}} \\ & + (\pi^+ - \pi_{\text{LMP}}) z_j^{\text{NEM-p}}\Big) - \mathcal{C}, \end{aligned}$$

where $\mathcal{C}$ is the network operation cost of the utility, and $z_i^{\text{NEM-p}} = d_i^{\text{NEM-p}} - g_i$ denotes net consumption of passive producer i with $d_i^{\text{NEM-p}}$ defined in (9). For simplicity, we here assume $N\pi^0 = \mathcal{C}$.

From (8), the surplus of passive producing and consuming prosumers are $S_i^{\text{NEM-p}}$ and $S_j^{\text{NEM-p}}$, respectively. The profit-neutral regulator/utility will construct the NEM X tariff by solving a Ramsey pricing problem proposed in Alahmed and Tong (2022b), which is given by

$$\begin{aligned} \max_{\pi^+, \pi^-} \quad & \textstyle\sum_i S_i^{\text{NEM-p}} + \sum_j S_j^{\text{NEM-p}} \\ s.t. \quad & S^{\text{NEM-u}}(\pi^+, \pi^-) = 0, \end{aligned} \qquad (16)$$

where the utility company maximizes the social welfare of all participants given that the regulated utility achieves revenue adequacy and profit neutrality.

4.2. One-part pricing over producers

The optimal DERA one-part pricing scheme is proposed by Alshehri-Ndrio-Bose-Basar (ANBB) (Alshehri et al., 2020), where the producer i can choose to sell energy to DERA with price λ_i. In this case, the surplus of a passive producer i can be computed by

$$S_i^{\text{ANBB-p}}(g_i) = \begin{cases} U_i(d_i^{\text{NEM-p}}) - \lambda_i z_i^{\text{NEM-p}} & z_i^{\text{NEM-p}} < 0 \\ U_i(d_i^{\text{NEM-p}}) - \pi^+ z_i^{\text{NEM-p}}, & z_i^{\text{NEM-p}} \geq 0 \end{cases}$$

Therefore, the injection power to the grid will be paid by λ_i under DERA and the withdrawal power from the grid will be charged by π^+ under the utility.

The profit maximization of the DERA to get the optimal one-part pricing $\boldsymbol{\lambda}$ is given by

$$\begin{aligned} \max_{\boldsymbol{\lambda}} \quad & \textstyle\sum_j (\pi_{\text{LMP}} - \lambda_i)[g_i - d_i^{\text{NEM-p}}]^+ \\ s.t. \quad & \mathcal{K}_i \leq \lambda_i [g_i - d_i^{\text{NEM-p}}]^+ + U_i(d_i^{\text{NEM-p}}). \end{aligned} \qquad (17)$$

Note that the original proposed optimal pricing scheme aims at keeping the surplus of active producers under DERA competitive with that when customers directly participate in the wholesale market as consumers. Here we adjust the DERA one-part pricing model to be $\mathcal{K}$*-competitive* over passive customers for the fairness of comparison. To make the DERA competitive to the NEM X retail program with the surplus of passive computed in (8), we have $\mathcal{K}_i = (1+\frac{\zeta}{100})S_i^{\text{NEM-p}}$. Therefore, the optimal profit of DERA computed from (17) is given by

$$S^{\text{ANBB-p}} = \sum_i(\pi_{\text{LMP}} - \frac{(100+\zeta)\pi^-}{100})[z_i^{\text{NEM-p}}]^- - \frac{\zeta U_i(d_i^{\text{NEM-p}})}{100},$$

which is independent of λ_i.

4.3. Two-part pricing over producers

The optimal DERA two-part pricing scheme (μ^1, μ_i^2) is proposed by Gao-Alshehri-Birge (GAB) (Gao et al., 2021). Similarly, here we adjust it to be $\mathcal{K}$*-competitive* over passive customers for the fairness of comparison. In this case, the surplus of a passive producer under DERA can be computed from

$$S_i^{\text{GAB-p}}(g_i) = \begin{cases} U_i(d_i^{\text{NEM-p}}) - \mu^1 z_i^{\text{NEM-p}} - \mu_i^2, & z_i^{\text{NEM-p}} < 0 \\ U_i(d_i^{\text{NEM-p}}) - \pi^+ z_i^{\text{NEM-p}}, & z_i^{\text{NEM-p}} \geq 0 \end{cases}$$

And the profit maximization of the DERA is

$$\begin{aligned} \max_{\mu^1, \boldsymbol{\mu}^2} \quad & \textstyle\sum_i(\mu_i^2 \mathbf{1}\{z_i^{\text{NEM-p}} < 0\} - (\pi_{\text{LMP}} - \mu^1) z_i^{\text{NEM-p}}) \\ s.t. \quad & \mathcal{K}_i \leq U_i(d_i^{\text{NEM-p}}) + \mu^1 [z_i^{\text{NEM-p}}]^- - \mu_i^2. \end{aligned} \tag{18}$$

Similarly, to make DERA competitive to NEM X, we have $\mathcal{K}_i = (1+\frac{\zeta}{100})S_i^{\text{NEM-p}}$. In this case, the optimal profit of the DERA computed from (18) is the same as that from (17), which is independent of (μ^1, μ_i^2).

4.4. Community choice aggregation

Based on current market rules, prosumers can participate in a community choice aggregation (CCA) to reduce energy bills by collectively pooling solar (or any other DER) within the community. A profit-neutral CCA model is proposed by Chakraborty et al. (2018). For a passive prosumer participating in a CCA with net consumption $z_n^{\text{NEM-p}}$, the prosumer surplus is given by

$$S_n^{\text{CCA-p}}(g_n) = \begin{cases} U_n(d_n^{\text{NEM-p}}) - \pi^- z_n^{\text{NEM-p}} - \pi^0, & z_{\text{CCA}} \leq 0 \\ U_n(d_n^{\text{NEM-p}}) - \pi^+ z_n^{\text{NEM-p}} - \pi^0, & z_{\text{CCA}} > 0 \end{cases},$$

where $z_{\text{CCA}} := \sum_n z_n^{\text{NEM-p}}$. This means all CCA customers will be charged by π^- if they sum up to be net producing ignoring the individual net-production/ net consumption state.

5. Case Studies

Seven cases were considered in case studies with participation model of prosumers shown in Sec.2 and Sec. 4. In Case 1, all prosumers were with a utility company offering NEM X with (16) (Alahmed and Tong, 2022b). In Case 2-7, 50% prosumers were with a utility company while the other prosumers chose the CCA[5] or DERA[6]. In Case 2, the CCA with the allocation rule proposed by Chakraborty et al. (2018) was considered, for which details are explained in Sec. 4.4. In Case 3, the DERA with the two-part pricing model (18) proposed by Gao et al. (2021) (GAB) was considered. And the one-part pricing proposed by Alshehri et al. (2020) (ANBB) was considered in Case 4 with (17). The original GAB and ANBB pricing were designed to be competitive with the model when the prosumers directly participates in the wholesale electricity market as a consumer. Here we modified the two pricing models to be competitive with the utility offered NEM X tariff. The competitive DERA model we proposed was implemented with $\mathcal{K}_n = (1+\frac{\zeta}{100})S_n^{\text{NEM-p}}$, $\mathcal{K}_n = (1+\frac{\zeta}{100})S_n^{\text{CCA-p}}$, and $\mathcal{K}_n = (1+\frac{\zeta}{100})S_n^{\text{GAB-p}}$ in Case 5, Case 6 and Case 7 to be competitive with NEM X, CCA and GAB[7]. In Case 1 and Case 5-7, the utility company had the same retail tariff. In Case 2-4, the utility company recomputed the NEM X tariff with the Ramsey pricing model to maintain profit neutral considering the coexistence of CCA and DERA. Normalized surplus of DERA, consumer, producer, and utility are analyzed.

5.1. Parameter settings

The simulation included N passive prosumer households indexed by n with a homogeneous concave quadratic utility function given by

$$U_n(x) = \begin{cases} \alpha x - \beta/2x^2, & 0 \leq x \leq \frac{\alpha}{\beta} \\ \frac{\alpha^2}{2\beta}, & x > \frac{\alpha}{\beta} \end{cases}, \forall n, \tag{19}$$

[5]Notation CCA here specifically represents the scheme from Chakraborty et al. (2018).

[6]We assumed 10% customers under the CCA/DERA are producers

[7]Mathematical formulations of $S_n^{\text{CCA-p}}$ and $\text{S}_n^{\text{GAB-p}}$ are shown in Sec.4, representing prosumer surpluses under CCA and GAB.

where we had $\alpha = \beta = 0.24$ based on parameter settings from Samadi et al. (2012). Let γ represent the percentage of producers among utility companies' customers, and $1-\gamma$ the percentage of consumers. We used $\pi_{\text{LMP}} = \$0.03$/kWh for the wholesale market LMP (CAISO, 2022), and $\pi^0 = \$0$, $\pi^+ = \pi^- + \$0.03$/kWh for NEM X tariff (Alahmed and Tong, 2022b). Assume $V_{kn}^{-1}(\pi), V_{kn}^{-1}(\pi^+), V_{kn}^{-1}(\pi^-) \in [\underline{d}_{kn}, \bar{d}_{kn}], \forall k, n$ for the consumption boundaries constraints from device k of prosumer's n. By setting $\zeta = 10$, we set the prosumer surplus markup at 10% above the competing aggregation methods. Letting DG generation $g_n \in (0, 5]$ kWh and $\gamma \in [0, 1]$, we evaluated the normalized DERA surplus, utility surplus, and customer surplus in Fig.2.

5.2. Simulation results

5.2.1. Surplus of DERA & CCA We observed from the first row of Fig.2 that the proposed competitive DER aggregation achieved larger DERA surpluses than other cases. In Case 5, the maximum DERA surplus over all cases was reached. The reason that DERA surpluses in Case 6 and 7 were smaller than that in Case 5 was that DERA in Case 6 and 7 needed to provide more prosumer surpluses to be competitive with CCA and GAB rather than NEM X.

Additionally, DERA was shown to be revenue adequate in the proposed model, but GAB and ANBB in Case 3 and 4 had negative DERA surplus when aggregating passive producers. It's also validated that the proposed CCA allocation rule from Chakraborty et al. (2018) guaranteed the profit neutrality for a municipal aggregation in Case 2.

5.2.2. Surplus of producers and consumers The second and third rows of Fig.2 show the surplus of consumers and producers, respectively. As required by the proposed competitive DERA model, DERA in Case 5-7 provided extra ζ% prosumer surpluses compared with the competitive objectives in Case 1-4. And, in Case 2 and 3, it's observed that prosumers in CCA and DERA had more surpluses that those under NEM X in Case 1. Additionally, with the increasing DG adoptions, the percentage of producers in the system, *i.e.,* γ, increased, and all prosumers received more surpluses in all cases.

5.2.3. Surplus of utility We can observe from the forth row of Fig.2 that the surplus of utility was zero in all cases. In Case 1 and Case 5-7, we assumed that the utility company adopted Ramsey pricing to compute

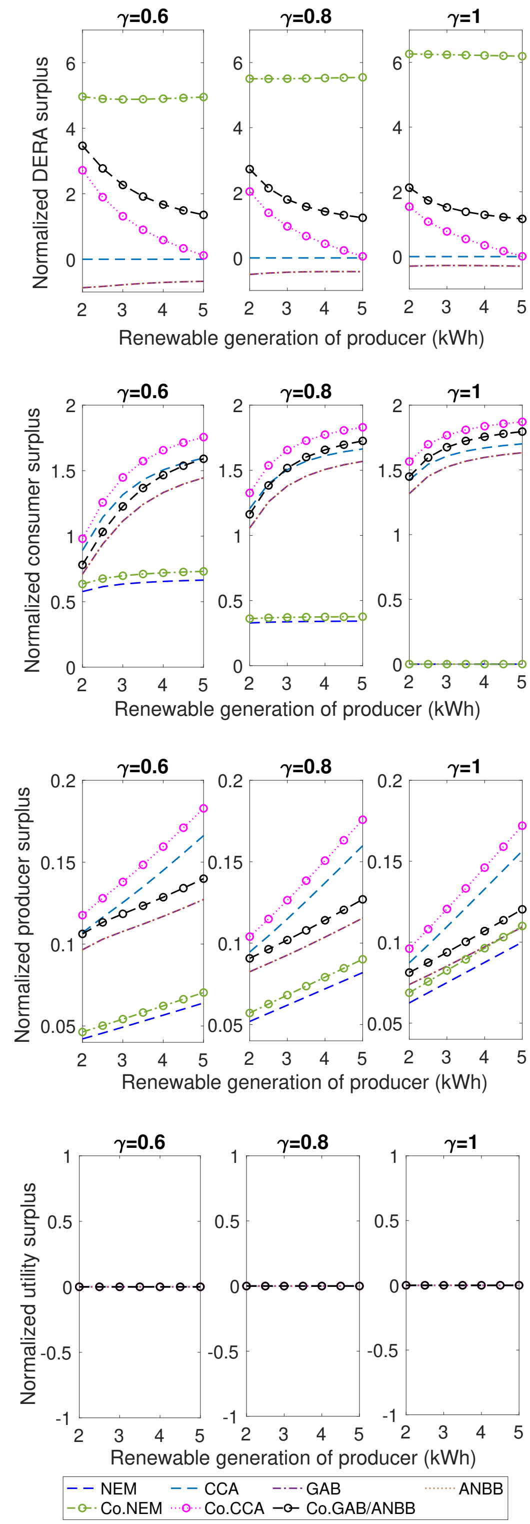

Figure 2. Welfare distribution.

π^+ and π^-, where the surplus of utility equaled zero (Alahmed and Tong, 2022b). From the set up of the Case 2-4, we known that the utility adjusted the retail tariff, considering the coexistence of CCA and DERA and maintained profit neutrality. Additionally, it's assumed that the fixed charge of the utility company equals to the fixed costs for the distribution network maintenance, outage services, etc. Therefore, we had profit neutral utility company in all cases.

5.3. DERA bids in the wholesale market

Based on Sec.3, the proposed DERA model had price-quantity bids for a price taker DERA into the wholesale electricity market by submitting the truthful supply function computed from (15), which was

$$\mathscr{S}(\pi) = \begin{cases} G - \frac{N(\alpha-\pi)}{\beta}, & \pi \leq \alpha \\ G, & \pi > \alpha \end{cases}, \tag{20}$$

where $G = \sum_{n=1}^{N} g_n$ was the aggregated renewable generation. And the optimal DERA bidding curve[8] when $N = 1000$ was shown in Fig.3. In a competitive wholesale market, DERA revealed those price-quantity curves truthfully to ISO. The slope was determined by parameters of the prosumer utility function β and the number of aggregated prosumers N. The intersection of the bidding curve with the y-axis was $(0, \alpha - \frac{\beta G}{N})$. For

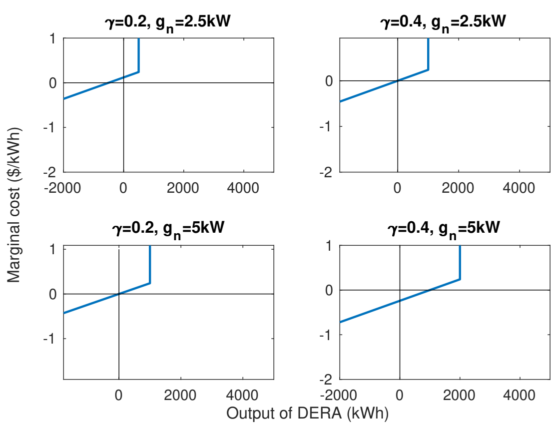

Figure 3. Optimal Bidding curve for price taker DERA.

all price-quantity bids with different parameter settings for γ and g_n, DERA with the proposed competitive aggregation model can generate to the maximum of G kW. In the bottom right of Fig. 3, the intersection of the DERA bidding curve with the y-axis is negative when $\alpha - \frac{\beta G}{N} < 0$. This means that the DERA chose to generate even under a negative market clearing price when it had redundant renewable energy to be injected into the power network. And in the top left of Fig. 3, the intersection of the DERA bidding curve with the y-axis is positive when $\alpha - \frac{\beta G}{N} > 0$. This means DERA preferred to withdraw energy from the power network under low market clearing price because of the lack of DER generation internally.

[8]The DERA bidding curve is the inverse of the supply function.

6. Conclusions

This paper considers the *competitive DER aggregation* of a profit-seeking DERA in the wholesale electricity market. It is by design that the proposed competitive DER aggregation model has the maximal surplus, and it can provide competitive services to its customers with higher surpluses than those offered by the distribution utility company and community choice aggregation. Many researchers establish the optimal prosumer consumption of DERA as a function of the local behind-the-meter (BTM) distributed generation (DG). This would complicate the way for DERA to construct offers/bids in the wholesale electricity market because offers/bids must be submitted before the realization of BTM DG. Fortunately, such a concern is unwarranted in this paper as the optimal prosumer consumption is independent of the BTM DG in the proposed DER aggregation optimization. Additionally, we derive the optimal price-quantity bid of the price-taking DERA in the wholesale market, which ensures that, once the wholesale market LMP is realized, the scheduled consumption is optimal. Therefore, DERA does not need an accurate price forecast to conduct optimal scheduling and pricing plans over the aggregated prosumers. Note that, the proposed optimal price-quantity bid only depends on the aggregated renewable generation and the aggregated optimal prosumer consumption. In practice, the aggregated renewable generation can be approximated by using historical data or the Law of Large Numbers, which is easier to be predicted than individual local BTM DG.

Establishing DER aggregation in practice must take into account many factors, including congestions of distribution networks, influences of market regulations, scheduling plans over multiple time intervals, and so on. These are directions to be considered in our future research (Chen et al., 2022) on this topic.

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