Operating-Envelopes-Aware Decentralized Welfare Maximization for Energy Communities

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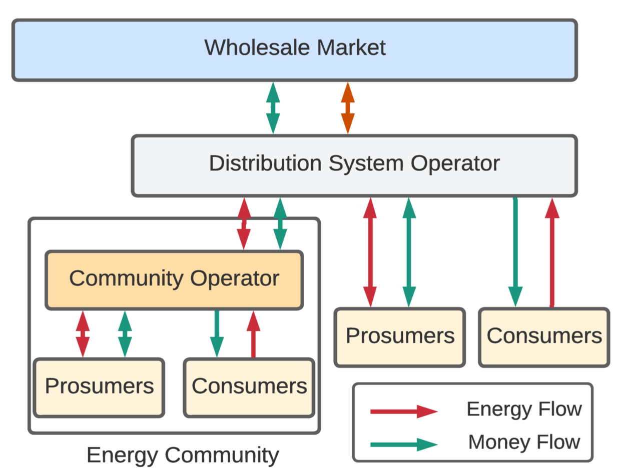
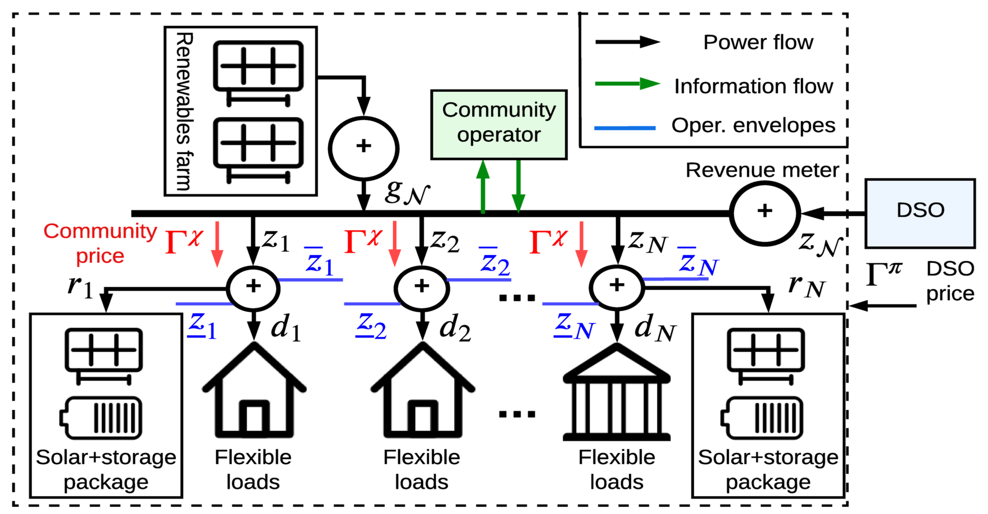
Energy Communities, Operating Envelopes, and Net Metering

Energy communities: Enablers of wider DER accessibility and aggregation

An energy community is a coalition of a group of customers who pool and aggregate their DER and perform energy and monetary transactions with the DSO as a single entity behind a PCC.

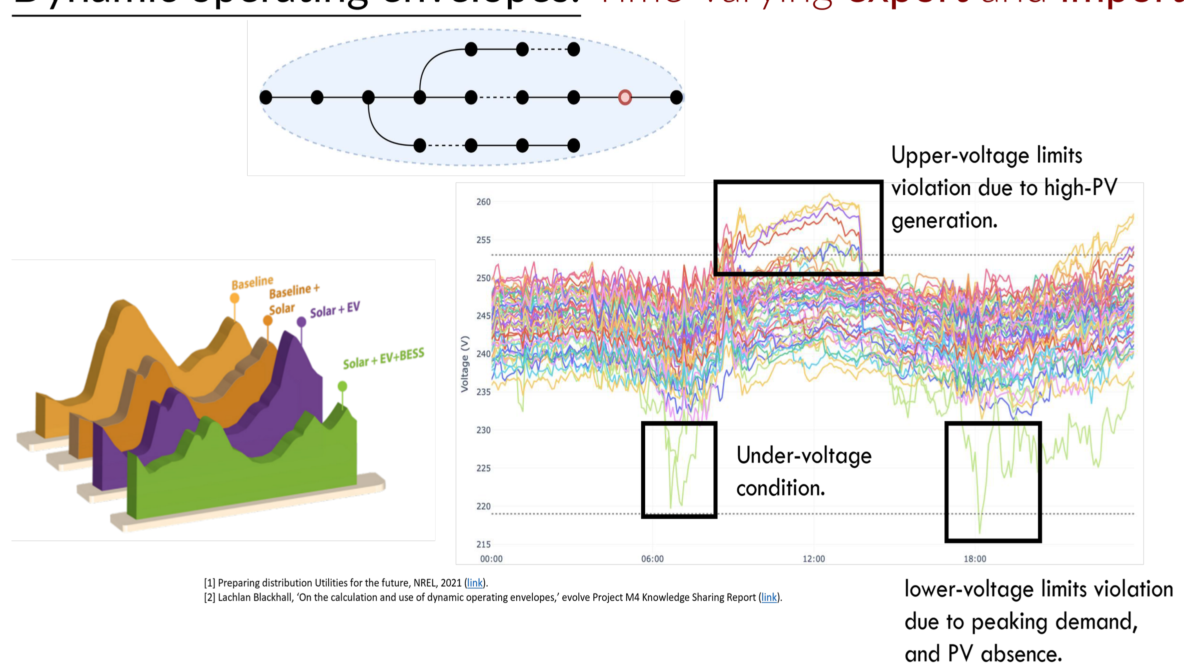


(a) ISO–DSO–Community Interface.



(b) Energy community framework.

Dynamic operating envelopes: Time-varying **export** and **import** limits at prosumers' PCCs



Usually, there is a mismatch between the intervals of peak DER imports and exports.

The un-coordinated BTM DER profiles are neither controllable nor visible by the DSO.

Dynamic operating envelopes (OEs) are proposed to enable DSOs to ensure network integrity (i.e., voltage and thermal limits), without directly controlling BTM DER or aggregators.

Net energy metering (NEM):

Under NEM, the utility revenue meter measures the community's net consumption and assigns a *buy (retail) rate* π^+ if the community is *net-importing*, and a *sell (export) rate* π^- if the community is *net exporting* – i.e., given the NEM X parameter $\pi = (\pi^+, \pi^-)$ the *community payment* $P^\pi_{\mathcal{N}}$ is

$$P^\pi_{\mathcal{N}}(z_{\mathcal{N}}) = \pi^+[z_{\mathcal{N}}]^+ - \pi^-[z_{\mathcal{N}}]^-, \quad \text{where} \quad z_{\mathcal{N}} := \sum_{i\in\mathcal{N}} z_i = d_{\mathcal{N}} + \underbrace{r_{\mathcal{N}} - g_{\mathcal{N}}}_{-b_{\mathcal{N}}} = d_{\mathcal{N}} - b_{\mathcal{N}}.$$

Prosumer surplus: *Surpluses of a community member* S^χ_i and its benchmark under DSO S^π_i are

$$S^\chi_i(z_i, b_{\mathcal{N}}) := \underbrace{U_i(\boldsymbol{d}_i)}_{\text{utility of cons.}} - \underbrace{P^\chi(z_i, b_{\mathcal{N}})}_{\text{payment under } \chi}, \quad S^\pi_i(z_i) := U_i(\boldsymbol{d}_i) - P^\pi(z_i), \quad \forall i \in \mathcal{N}.$$

Each member's consumption $\boldsymbol{d}_i \in [\underline{\boldsymbol{d}}_i, \overline{\boldsymbol{d}}_i] \subseteq \mathbb{R}^K_+$ & net consumption $z_i \in [\underline{z}_i, \overline{z}_i] \subseteq \mathbb{R}$ are bounded.

Contributions/Summary of Results

We propose a OEs-aware, prosumer centric, and welfare-maximizing market mechanism for energy communities that aggregates individual and shared community resources under a general NEM policy. The proposed market mechanism:

- ★ incorporates the DSO-imposed OEs, ensuring a network-aware community operation.
- ★ guarantees surplus levels to its members higher than the maximum surplus under DSO.
- ★ decentrally achieves welfare optimality.
- ★ satisfies the generalized *cost-causation principle*.

Decentralized Welfare Optimality

The comm. welfare is decentrally maximized if the *max. welfare under centralized operation* $W^*_{\mathcal{N}}$,

$$\begin{aligned}
\mathcal{P}^\chi_{\mathcal{N}}:\ & \underset{\{\boldsymbol{d}_i\}_{i=1}^N, \{z_i\}_{i=1}^N}{\text{Maximize}} \quad W^\chi_{\mathcal{N}} := \textstyle\sum_{i\in\mathcal{N}} S^\chi_i(z_i, b_{\mathcal{N}}) && \\
& \text{subject to } S^\chi_i(z_i, b_{\mathcal{N}}) = U_i(\boldsymbol{d}_i) - P^\chi_i(\cdot), \forall i \in \mathcal{N} && \text{(member surplus)}\\
& \textstyle\sum_{i\in\mathcal{N}} P^\chi(z_i, b_{\mathcal{N}}) = P^\pi_{\mathcal{N}}(z_{\mathcal{N}}) && \text{(operator profit neutrality)}\\
& z_{\mathcal{N}} = \textstyle\sum_{i\in\mathcal{N}} z_i = \sum_{i\in\mathcal{N}} \boldsymbol{1}^\top \boldsymbol{d}_i - b_{\mathcal{N}} && \text{(Aggregate net-consumption)}\\
& \underline{\boldsymbol{d}}_i \preceq \boldsymbol{d}_i \preceq \overline{\boldsymbol{d}}_i, \forall i \in \mathcal{N} && \text{(Flexible consumption limits)}\\
& \underline{z}_i \preceq z_i \preceq \overline{z}_i, \forall i \in \mathcal{N} && \text{(Operating envelopes)}
\end{aligned}$$

is achieved by the aggregate maximum surpluses of community members under the proposed market mechanism, i.e., if

$$W^*_{\mathcal{N}} = \sum_{i\in\mathcal{N}} S^{*,\chi}_i(z^{*,\chi}_i, \boldsymbol{b}), \tag{1}$$

where $S^{*,\chi}_i(z^{*,\chi}_i, \boldsymbol{b})$ is the *maximum surplus of member* $i \in \mathcal{N}$ under the proposed mechanism χ, which is achieved by its *optimal net consumption* schedule $z^{*,\chi}_i$.

Operating-Envelope-Aware Market Mechanism

The threshold-based, OEs-aware, pricing policy $\Gamma^\chi(\cdot)$ (payment rule $P^\chi(\cdot)$) is given by the 3-tuple tariff parameter $\chi = (\pi^+, \pi^z(\boldsymbol{b}), \pi^-)$ with the order $\pi^+ \geq \pi^z(\boldsymbol{b}) \geq \pi^-$, as

$$\underbrace{\Gamma^\chi(\boldsymbol{b})}_{\text{Pricing rule}} = \begin{cases} \pi^+ & , b_{\mathcal{N}} < \sigma_1(\boldsymbol{b}) \\ \pi^z(\boldsymbol{b}) & , b_{\mathcal{N}} \in [\sigma_1(\boldsymbol{b}), \sigma_2(\boldsymbol{b})] \\ \pi^- & , b_{\mathcal{N}} > \sigma_2(\boldsymbol{b}) \end{cases}, \qquad \underbrace{P^\chi(z_i, \boldsymbol{b})}_{\text{payment rule}} = \Gamma^\chi(\boldsymbol{b}) \cdot z_i, \tag{2}$$

where the thresholds $\sigma_1(\boldsymbol{b})$ and $\sigma_2(\boldsymbol{b})$ are computed as $(\sigma_2(\boldsymbol{b}) \geq \sigma_1(\boldsymbol{b}))$

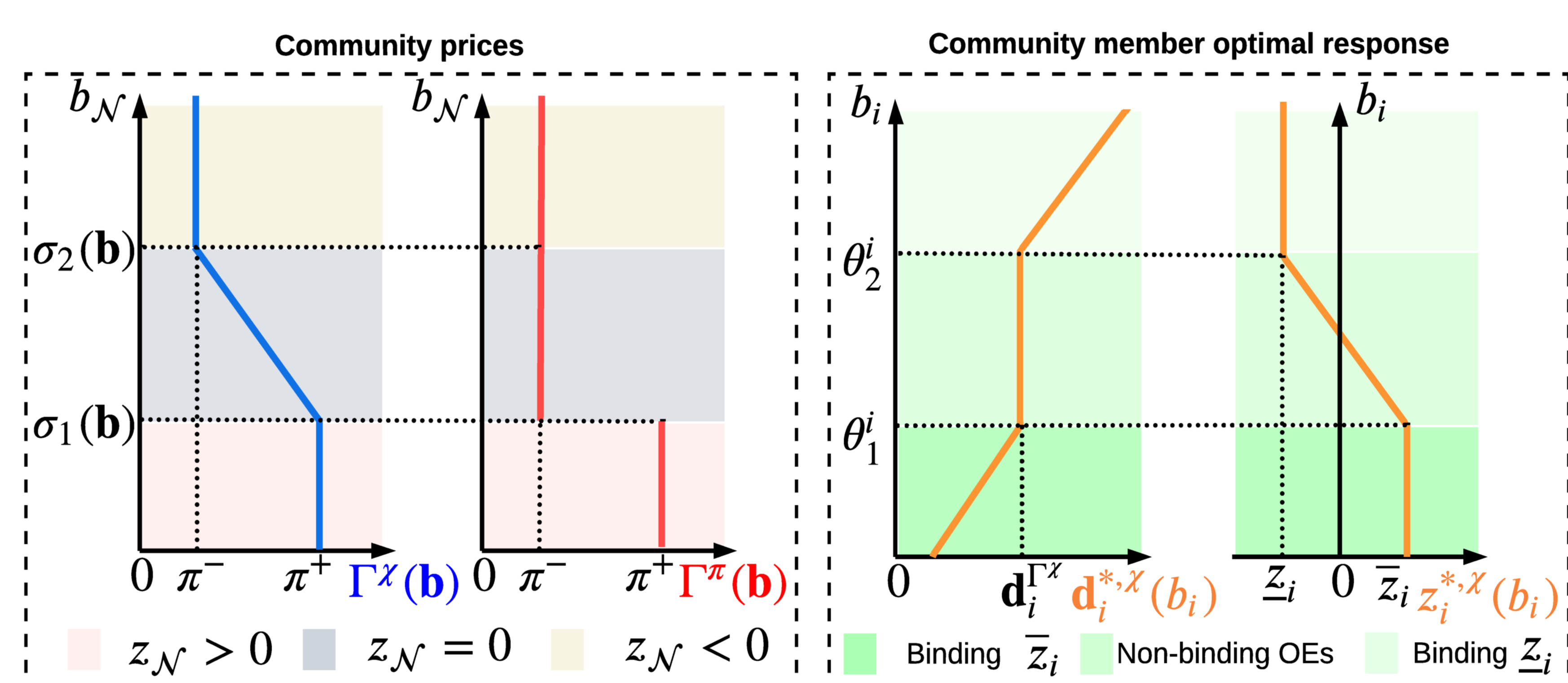
$$\sigma_1(\boldsymbol{b}) := \sum_{i=1}^N \max\{\underline{z}_i + b_i, \min\{R^+_i, \overline{z}_i + b_i\}\}, \quad \sigma_2(\boldsymbol{b}) := \sum_{i=1}^N \max\{\underline{z}_i + b_i, \min\{R^-_i, \overline{z}_i + b_i\}\}, \tag{3}$$

with

$$R^+_i := \boldsymbol{1}^\top \max\{\underline{\boldsymbol{d}}_i, \min\{\boldsymbol{f}_i(\boldsymbol{1}\pi^+), \overline{\boldsymbol{d}}_i\}\}, \quad R^-_i := \boldsymbol{1}^\top \max\{\underline{\boldsymbol{d}}_i, \min\{\boldsymbol{f}_i(\boldsymbol{1}\pi^-), \overline{\boldsymbol{d}}_i\}\}. \tag{4}$$

The price $\pi^z(\boldsymbol{b}) := \mu^*(\boldsymbol{b})$ is the solution of

$$\sum_{i\in\mathcal{N}} \max\{\underline{z}_i + b_i, \min\{R^z_i(\mu), \overline{z}_i + b_i\}\} = b_{\mathcal{N}}, \quad \text{where} \quad R^z_i(\mu) := \boldsymbol{1}^\top \max\{\underline{\boldsymbol{d}}_i, \min\{\boldsymbol{f}_i(\boldsymbol{1}\mu), \overline{\boldsymbol{d}}_i\}\}. \tag{5}$$



Market mechanism structural properties: ① Resource and OEs aware pricing ② Threshold-based structure partitioning the range of $b_{\mathcal{N}}$ into 3 zones ③ Non-discriminatory pricing ④ Supply/Demand balance ⑤ Endogenously-determined market roles ⑥ Scalable and explainable.

Community Member Problem

Given $b_{\mathcal{N}}$, the community pricing and payment rules are announced, and accordingly, every $i \in \mathcal{N}$ member solves the following surplus maximization program:

$$(\boldsymbol{d}^{*,\chi}_i, z^{*,\chi}_i) = \underset{\boldsymbol{d}_i\in\mathbb{R}^K_+, z_i\in\mathbb{R}}{\text{argmax}} \ S^\chi_i(\boldsymbol{d}_i, z_i) := U_i(\boldsymbol{d}_i) - P^\chi(z_i, \boldsymbol{b}) \quad \text{subject to} \quad z_i := \boldsymbol{1}^\top \boldsymbol{d}_i - b_i, \quad \underline{\boldsymbol{d}}_i \preceq \boldsymbol{d}_i \preceq \overline{\boldsymbol{d}}_i, \quad \underline{z}_i \leq z_i \leq \overline{z}_i. \tag{6}$$

Lemma: The optimal decisions obey by a two-threshold ($\theta^i_1 := \boldsymbol{1}^\top \boldsymbol{d}^{\Gamma\chi}_i - \overline{z}_i, \theta^i_2 := \boldsymbol{1}^\top \boldsymbol{d}^{\Gamma\chi}_i - \underline{z}_i$) policy that partitions b_i into three zones as shown in the community member optimal response panel. The consumption $\boldsymbol{d}^\Gamma_i = \max\{\underline{\boldsymbol{d}}_i, \min\{\boldsymbol{f}_i(\boldsymbol{1}\Gamma(\boldsymbol{b}), \overline{\boldsymbol{d}}_i\}\}$.

Theoretical Findings

Theorem 1: Individual rationality

Under the proposed market mechanism, every $i \in \mathcal{N}$ member achieves a surplus no less than its benchmark, i.e., $S^{*,\chi}_i(z^{*,\chi}_i, \boldsymbol{b}) \geq S^{*,\pi}_i(b_i)$.

Theorem 2: Decentralized welfare optimality under χ

Under the OEs-aware market mechanism, the aggregate surplus of community members achieves the community maximum welfare, i.e., $\sum_{i\in\mathcal{N}} S^{*,\chi}_i(z^{*,\chi}_i, \boldsymbol{b}) = W^*_{\mathcal{N}}(\boldsymbol{b})$.

Theorem 3: Cost-causation conformity

The proposed OEs-aware market mechanism satisfies the **generalized cost-causation principle**: ① profit-neutrality, ② equity, ③ individual rationality, ④ monotonicity, ⑤ cost-causation penalty, and ⑥ cost mitigation reward.

Simulation Results

Simulation settings:

- $N = 20$ residential households.
- All households have flexible consumption.
- 17/20 members have rooftop solar.
- DSO NEM X has ToU buy rate $\pi^+_{\text{ON}} =$ \$0.40/kWh and $\pi^+_{\text{OFF}} =$ \$0.20/kWh, and the sell rate π^- is at the wholesale price.
- Quadratic concave $U(\cdot)$.

The figures show community member monthly surplus gain (%) over benchmark and monthly bill (\$), both under two OEs $-\underline{z}_i = \overline{z}_i = 3$kW (left) and $-\underline{z}_i = \overline{z}_i = \infty$ (right). The bar chart shows the percentage of time under which $sign(z^{*,\chi}_i) \neq sign(z^*_{\mathcal{N}})$.