Achieving Social Optimality for Energy Communities via Dynamic NEM Pricing

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2023 IEEE Power & Energy Society General Meeting (PESGM) | 978-1-6654-6441-3/23/$31.00 ©2023 IEEE | DOI: 10.1109/PESGM52003.2023.10253295

***Abstract*—We propose a social welfare maximizing mechanism for an energy community that aggregates individual and shared community resources under a general net energy metering (NEM) policy. Referred to as Dynamic NEM, the proposed mechanism adopts the standard NEM tariff model and sets NEM prices dynamically based on the total shared renewables within the community. We show that Dynamic NEM aligns the individual member's incentive with that of the overall community; each member optimizing individual surplus under Dynamic NEM results in maximum community's social welfare. We further show that Dynamic NEM guarantees a higher benefit to each community member than possible outside the community. Dynamic NEM is also shown to satisfy the cost-causation principle. Empirical studies using real data on a hypothetical energy community demonstrate the benefits to community members and grid operators.**

***Index Terms*—distributed energy resources aggregation, energy community, net metering, pricing mechanism.**

I. Introduction

Energy communities are regarded as a solution that improves system efficiency, economies of scale, and equity while enabling distributed energy resources (DER) aggregation and wider technology accessibility [2]–[4]. A generic *energy community* is illustrated in Fig.1, where a coalition of a group of customers pool and aggregate their resources within the community and perform energy and monetary transactions with the utility company as a single entity behind a point of common coupling (PCC) downstream of the utility revenue meter [4]. Under the widely adopted NEM policy, the utility revenue meter measures the community's net consumption and assigns a *buy (retail) rate* if the community is net importing, and a *sell (export) rate* if the community is net exporting [5]. Several utilities have initiated energy-community-enabling programs, such as NEM aggregation (NEMA)[1], for university campuses, residential complexes, and medical cities.

We focus in this work on the pricing mechanism that determines each community member's payment based on her consumption, individual-owned renewable, and her share of the community-owned DER. We set the underlying pricing principle as maximizing community social welfare while ensuring that each member gains higher benefits than possible outside the community. To this end, we subject the pricing mechanism to the cost-causation rule.

This work was supported in part by the National Science Foundation under Awards 1932501 and 2218110.

The full paper, including proofs of theoretical results, is available in [1].

[1]See for example, Pacific Gas and Electric company (PG&E), California, and Baltimore Gas and Electric Company (BGE), Maryland.

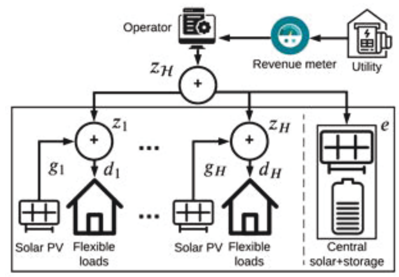

Fig. 1. Energy community framework. Member consumption and renewables are $d_i, g_i \in \mathcal{R}_+$, respectively, and member net consumption, centralized resources, and aggregate net consumption are $z_i, e, z_{\mathcal{H}} \in \mathcal{R}$, respectively.

A. Related Work

There is a rich literature on energy communities covering optimal energy management [6], market mechanisms [3], [7], and coordination frameworks [8]. Most relevant to this work is the intersection of community pricing and allocation rules [3], [7], and optimal resource scheduling for welfare/cost optimization [9], [10].

Three energy community models have been widely discussed, each offering a different market hierarchy and flexibility to its members. The first is the decentralized model with bidirectional financial/energy transactions, i.e., peer-to-peer (P2P) transactions [11], [12]. Through *bilateral contracts*, the P2P market structure gives full flexibility to its members to switch from being price-takers to price makers, depending on their own benefit functions. The P2P market structure is often challenged by policy and physical restrictions, data storage issues, and convergence to social optimality.

The second is the centralized model involving a community operator who schedules all resources for the benefit of the community [6], [13]. While this model has the potential to achieve the highest community overall benefits, it often comes with prohibitive computation costs and a lack of members' privacy. Also, maximizing the total community benefits may not align with the individual benefits of its members.

The third model, to which the work presented here belongs, is the individual scheduling of its own resources incentivized through the operator's pricing mechanism [7], [9], [10], [14]. The major challenge is to design a pricing mechanism that aligns rational individual decisions to community benefits in terms of achieving overall efficiency, access equity, and fairness in compensation. In [9], a bi-level optimization of an apartment building energy community with central generation and storage was formulated to analyze pricing and energy sharing. In [10], the energy cost of a solar+storage community was minimized and then allocated based on a Nash bargaining benefit-sharing model. Although the authors ensure cooperation stability under the possibility of strategic behaviors, complying with the cost-causation principle was not considered. The authors in [14] analyze a stochastic energy community model with cost-minimizing members. An algorithm is proposed for better estimation of the stochastic game. The pricing and allocations in [9], [10], [14] did not consider the conformity with the cost-causation principle.

The work of Chakraborty et al. [7] stands out as the first mechanism design under the cost-causation principle, which offers every community member a lower payment than would be outside the community. The Dynamic NEM mechanism proposed in this paper generalizes the approach in [7] to include individual surplus and community social welfare as part of the design objectives of the community pricing in a decentralized optimization framework. The consideration of community social welfare optimality necessitates designing a mechanism that not only devises payment rules as in [7], but also set pricing rules that induce community members to achieve the welfare optimality.

To our best knowledge, Dynamic NEM proposed here is the first community energy pricing mechanism that achieves efficiency under the cost-causation principle.

B. Summary of Results

We propose Dynamic NEM—a community pricing mechanism that sets the NEM price based on available DER. Dynamic NEM uses the same prices as the utility's NEM tariff, except that the import and export prices are imposed dynamically based on the gross renewables within the community rather than individual members' net consumption and the time-of-use in the utility's NEM tariffs.

The proposed Dynamic NEM generalizes the payment rule of [7] with two significant differences. First, Dynamic NEM prices are set *ex-ante* (rather than imposed *ex-post* in [7]) prior to elicit community members' response that achieves community social welfare maximization. Second, Dynamic NEM induces a community-level net-zero consumption zone where the shared renewables balance the total consumption.

We establish the following properties of Dynamic NEM:

- individual surplus maximization leads to maximum community social welfare.
- individual surplus under Dynamic NEM is higher than the maximum surplus under utility's NEM.
- the payment rule under Dynamic NEM satisfies cost-causation principle.

Our empirical results use real residential data to construct a hypothetical energy community, under which the benefits of community members and the grid operator are showcased.

II. Problem Formulation

To formulate the energy community, we consider a finite set of H community members, indexed by $i \in \mathcal{H} = \{1, 2, \ldots, H\}$, sharing their resources behind a PCC under NEM (Fig.1). The members are subject to operator's pricing mechanism. We assume that community members' decision process has the same timescale as that of the NEM billing period, which allows us to adopt a single time step formulation. For billing and pricing purposes, every member's generation and net consumption are assumed to be sub-metered.

A. Community Resources

We assume each member $i \in \mathcal{H}$ has K controllable devices, indexed by $k \in \mathcal{K} = \{1, 2, \ldots, K\}$, whose *energy consumption bundle* is denoted by

$$\boldsymbol{d}_i = (d_{i1}, \cdots, d_{iK}) \in \mathcal{D}_i := \{\boldsymbol{d}_i : \underline{\boldsymbol{d}}_i \preceq \boldsymbol{d}_i \preceq \overline{\boldsymbol{d}}_i\} \subseteq \mathcal{R}_+^K, \quad (1)$$

where $\underline{\boldsymbol{d}}_i, \overline{\boldsymbol{d}}_i$ are the consumption bundle's lower and upper limits of customer i, respectively. The *aggregate consumption* of the community is denoted by $d_{\mathcal{H}} := \sum_{i \in \mathcal{H}} \boldsymbol{1}^\top \boldsymbol{d}_i$.

Community members may own *renewable generation*, which we denote by $g_i \in \mathcal{R}_+$ for every $i \in \mathcal{H}$. The community's *aggregate gross generation* is $g_{\mathcal{H}} := \sum_{i \in \mathcal{H}} g_i$. Without loss of generality, centralized solar, with every $i \in \mathcal{H}$ member owning a share $x_i \in [0, 1]$, is ignored.

The *net-consumption* of every $i \in \mathcal{H}$ member $z_i \in \mathcal{R}$ and the *aggregate net-consumption* $z_{\mathcal{H}} \in \mathcal{R}$ are defined as

$$z_i := \boldsymbol{1}^\top \boldsymbol{d}_i - g_i, \quad z_{\mathcal{H}} := \sum_{i \in \mathcal{H}} z_i = d_{\mathcal{H}} - g_{\mathcal{H}}, \quad (2)$$

where $z_i \geq 0$ ($z_{\mathcal{H}} \geq 0$) and $z_i < 0$ ($z_{\mathcal{H}} < 0$) represent a *net-consuming* and *net-producing* member (community), respectively.

B. Community Payments

At the revenue meter (Fig.1), $z_{\mathcal{H}}$ is measured and billed based on the NEM X tariff proposed by [15]. Given the NEM X tariff parameter $\pi = (\pi^+, \pi^-, \pi^0)$, *community payment* is

$$P^\pi_{\mathcal{H}}(z_{\mathcal{H}}) = \pi^+ [z_{\mathcal{H}}]^+ + \pi^- [z_{\mathcal{H}}]^- + \pi^0, \quad (3)$$

where $[x]^+ := \max\{0, x\}$ and $[x]^- := \min\{0, x\}$ denote the positive and negative part functions for any $x \in \mathcal{R}$, respectively, and $\pi^+, \pi^-, \pi^0 \in \mathcal{R}_+$ are the *retail rate*, *export rate*, and *fixed charge*, respectively. We assume $\pi^- \leq \pi^+$.

For every $i \in \mathcal{H}$, the payment after joining the community $P_i^{\pi_c}(\cdot)$ is determined by the payment rule with the parameter π_c. The payment before joining the community, i.e., under the utility's NEM X regime, is considered as the *benchmark payment* given by [15] as

$$P_i^\pi(z_i) = \pi^+ [z_i]^+ + \pi^- [z_i]^- + \pi^0 / H. \quad (4)$$

We assume π^0 is uniformly recovered by the H members.

C. Community Pricing Mechanism

We generalize the axiomatic community pricing framework to ensure equity and efficiency [7]. In particular, we are interested in community payment rules that satisfy the axioms of: 1) *individual rationality*, 2) *profit-neutrality*, 3) *equity*, 4) *monotonicity*, 5) *cost-causation penalty* and 6) *cost-mitigation*

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reward. We relegate the formal statements of the axioms to the appendix in [1] and offer instead a non-mathematical description. *Individual rationality* is achieved when the customers are better off with the community. *Profit-neutrality* ensures that the benefit/losses of the community operator are entirely redistributed among its members, i.e. *budget-balance*. *Equity* is attained when the payments (compensations) of two community members with the same net consumption are equivalent. The *monotonicity* axiom ensures that having higher net consumption (net production) results in higher payment (compensation). Lastly, *cost-causation penalty* and *cost-mitigation reward* are met if members pay for causing costs and get rewarded for reducing costs, respectively.

The following definition uses the six axioms to establish conformity with the cost causation principle [7].

Definition 1 (Cost-causation principle)**.** *The pricing and payment rules meet the cost causation principle if axioms 1–6 are satisfied.*

D. Community Surplus and Welfare Optimization

For every $i \in \mathcal{H}$, the *community member surplus* $S_i^{\pi_c}(\cdot)$ and *benchmark surplus* $S_i^{\pi}(\cdot)$ are

$$S_i^{\pi_c}(\cdot) := U_i(\boldsymbol{d}_i) - P_i^{\pi_c}(\cdot),\ S_i^{\pi}(z_i) := U_i(\boldsymbol{d}_i) - P_i^{\pi}(z_i), \quad (5)$$

respectively, where the utility function $U_i(\boldsymbol{d}_i)$ is assumed to be additive, strictly concave, strictly increasing, and continuously differentiable with a marginal utility function $\boldsymbol{L}_i$. Therefore,

$$U_i(\mathbf{d}_i) := \sum_{k\in\mathcal{K}} U_{ik}(d_{ik}), \mathbf{L}_i := \nabla U_i = (L_{i1}, \ldots, L_{iK}). \quad (6)$$

Community welfare is defined as the sum of community members' surpluses $W_{\mathcal{H}}^{\pi} := \sum_{i\in\mathcal{H}} S_i^{\pi_c}(\cdot)$, which the operator maximizes by solving:

$$\begin{aligned} \mathcal{P}_{\mathcal{H}}: \quad & \underset{(\boldsymbol{d}_i,\ldots,\boldsymbol{d}_H)}{\text{Maximize}} && W_{\mathcal{H}}^{\pi} := \textstyle\sum_{i\in\mathcal{H}} S_i^{\pi_c}(\boldsymbol{d}_i, \cdot) \\ & \text{subject to} && S_i^{\pi_c}(\boldsymbol{d}_i, \cdot) = U_i(\boldsymbol{d}_i) - P_i^{\pi_c}(\cdot),\ \forall i \\ &&& \textstyle\sum_{i\in\mathcal{H}} P_i^{\pi_c}(\cdot) = P_{\mathcal{H}}^{\pi}(z_{\mathcal{H}}) \\ &&& z_{\mathcal{H}} = \textstyle\sum_{i\in\mathcal{H}}(\mathbf{1}^{\top}\boldsymbol{d}_i - g_i) \\ &&& \underline{\boldsymbol{d}}_i \preceq \boldsymbol{d}_i \preceq \bar{\boldsymbol{d}}_i,\ \forall i, \end{aligned} \quad (7)$$

where the second constraint is the *profit-neutrality* condition.

III. Dynamic NEM for decentralized welfare optimization

The community operator's primary task is to develop a pricing mechanism that induces community members to schedule their resources in a way that achieves overall welfare optimality while conforming with the cost-causation principle.

A. Optimal Community Pricing

The operator gathers every member's $i \in \mathcal{H}$ information $\mathcal{I}_i$ and uses $\mathcal{I} = \{\mathcal{I}_i, \ldots, \mathcal{I}_{\mathcal{H}}\}$ to solve (7), which is used to envisage the pricing mechanism[2].

[2]We assume that the community operator learns its members' inverse marginal utility functions and consumption limits.

Dynamic NEM. *The pricing policy for all $i \in \mathcal{H}$ members, is given by the 4-tuple parameter $\pi_c = (\pi^+, \pi^z(g_{\mathcal{H}}), \pi^-, \pi_c^0)$ with the order $\pi^+ \geq \pi^z(g_{\mathcal{H}}) \geq \pi^-$, where $\pi_c^0 = \pi^0/H$, and $\pi^z(g_{\mathcal{H}}) := \mu^*(g_{\mathcal{H}})$ is the solution of:*

$$\sum_{i\in\mathcal{H}}\sum_{k\in\mathcal{K}} \max\{\underline{d}_{ik}, \min\{f_{ik}(\mu), \bar{d}_{ik}\}\} = g_{\mathcal{H}}, \quad (8)$$

where $f_{ik} := L_{ik}^{-1}$ is the inverse marginal utility function for every $i \in \mathcal{H}, k \in \mathcal{K}$. The payment rule is given by

$$P_i^{\pi_c}(z_i, g_{\mathcal{H}}) = \begin{cases} \pi^+ z_i + \pi_c^0, & g_{\mathcal{H}} < d_{\mathcal{H}}^+ \\ \pi^z(g_{\mathcal{H}}) z_i + \pi_c^0, & g_{\mathcal{H}} \in [d_{\mathcal{H}}^+, d_{\mathcal{H}}^-] \\ \pi^- z_i + \pi_c^0, & g_{\mathcal{H}} > d_{\mathcal{H}}^-, \end{cases} \quad (9)$$

where

$$d_{\mathcal{H}}^+ := \sum_{i\in\mathcal{H}}\sum_{k\in\mathcal{K}} \max\{\underline{d}_{ik}, \min\{f_{ik}(\pi^+), \bar{d}_{ik}\}\} \quad (10)$$

$$d_{\mathcal{H}}^- := \sum_{i\in\mathcal{H}}\sum_{k\in\mathcal{H}} \max\{\underline{d}_{ik}, \min\{f_{ik}(\pi^-), \bar{d}_{ik}\}\} \geq d_{\mathcal{H}}^+. \quad (11)$$

1) Structural Properties of Dynamic NEM: The dynamic pricing policy has an appealing threshold-based resource-aware structure, that announces community prices based on the level of aggregate renewable generation compared to the two renewable-generation-independent thresholds $d_{\mathcal{H}}^+$ and $d_{\mathcal{H}}^-$. The thresholds arise from the community's optimal aggregate consumption $d_{\mathcal{H}}^*$ that solves (7), given in Theorem 1 as

$$d_{\mathcal{H}}^*(g_{\mathcal{H}}) = \max\{d_{\mathcal{H}}^+, \min\{g_{\mathcal{H}}, d_{\mathcal{H}}^-\}\}. \quad (12)$$

From (12), we note that $d_{\mathcal{H}}^+$ and $d_{\mathcal{H}}^-$ partition the range of $g_{\mathcal{H}}$ into three zones based on whether the community is 1) net-consuming ($z_{\mathcal{H}}^* > 0$), 2) net-producing ($z_{\mathcal{H}}^* < 0$) or 3) net-zero ($z_{\mathcal{H}}^* = 0$), where $z_{\mathcal{H}}^*(g_{\mathcal{H}}) := d_{\mathcal{H}}^* - g_{\mathcal{H}}$.

In the net-consuming and net-producing zones, the optimal community at the PCC faces the utility's π^+ and π^-, respectively, and directly passes these two prices to its members. When $g_{\mathcal{H}} \in [d_{\mathcal{H}}^+, d_{\mathcal{H}}^-]$, the community is energy-balanced $d_{\mathcal{H}}^*(g_{\mathcal{H}}) = g_{\mathcal{H}}$, and the volumetric charge is zero. It turns out that, in the net zero zone, it is optimal to charge members by the Lagrangian multiplier satisfying the Karush-Kuhn-Tucker (KKT) condition of the net zero zone – i.e., $d_{\mathcal{H}}^*(g_{\mathcal{H}}) = g_{\mathcal{H}}$. Therefore, the price $\pi^z(g_{\mathcal{H}})$ dynamically decreases with increasing $g_{\mathcal{H}}$ to incentivize demand increases, keeping the community off the grid.

2) Intuitions of Dynamic NEM: The pricing policy is economically intuitive as it responds to the increasing community local generation-to-demand ratio by dynamically reducing the price from π^+ to π^- through $\pi^z(g_{\mathcal{H}})$. Unlike their benchmarks in (4), who face the so-called *NEM 2.0* with different prices for imports and exports, community members under Dynamic NEM, have equivalent import and export rates, i.e., *NEM 1.0*.

Compared to their benchmark, net-producing community members under (9), are compensated at prices higher than π^- if the community is not net-producing $g_{\mathcal{H}} < d_{\mathcal{H}}^-$. Also, net-consuming members face prices lower than π^+, if the community is not net-consuming $g_{\mathcal{H}} > d_{\mathcal{H}}^+$. This also applies to *non-adopting* members (i.e., customers without DG).

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B. Individual optimization under Dynamic NEM

Given Dynamic NEM, every $i \in \mathcal{H}$ member maximizes its surplus (5) by optimally scheduling its consumption as

$$\mathcal{P}_i: \boldsymbol{d}_i^* = \underset{\boldsymbol{d}_i \in \mathcal{R}_+^K}{\operatorname{argmax}} \quad S_i^{\pi_c}(\cdot) := U_i(\boldsymbol{d}_i) - P_i^{\pi_c}\left(\mathbf{1}^\top \boldsymbol{d}_i - g_i\right)$$
$$\text{subject to} \quad \underline{\boldsymbol{d}}_i \preceq \boldsymbol{d}_i \preceq \overline{\boldsymbol{d}}_i. \tag{13}$$

The following theorem states that, under Dynamic NEM, the aggregate optimal surplus in (13) for all $i \in \mathcal{H}$ results in the maximum social welfare of (7).

Theorem 1 (Decentralized welfare maximization)**.** *Under Dynamic NEM, the community maximum welfare $W_{\mathcal{H}}^{*,\pi}$ is decentrally achieved, i.e., $W_{\mathcal{H}}^{*,\pi} = \sum_{i \in \mathcal{H}} S_i^{*,\pi_c}(z_i^*, g_{\mathcal{H}})$, where $z_i^* := \mathbf{1}^\top \boldsymbol{d}_i - g_i$ is member i's optimal net-consumption.* □

Dynamic NEM, not only induces members to achieve welfare optimality, but grants them surplus levels higher than their maximum surplus under the utility's NEM X $S_i^{*,\pi}(g_i)$ [5].

Theorem 2 (Individual rationality)**.** *Under Dynamic NEM, every $i \in \mathcal{H}$ member is better off with the community, i.e., $S_i^{*,\pi_c}(z_i^*, g_{\mathcal{H}}) \geq S_i^{*,\pi}(g_i)$.* □

Worth noting is that Theorem 2 applies to non-DG adopting members too, because $S_i^{*,\pi_c}(\boldsymbol{d}_i^*, g_{\mathcal{H}}) \geq S_i^{*,\pi}(0)$. As a result of Theorem 2, the welfare of the community is higher than its benchmark of H *optimal* standalone customers under the utility's NEM X – i.e., $W^{*,\pi}(g_{\mathcal{H}}) \geq \sum_{i \in \mathcal{H}} S_i^{*,\pi}(g_i)$.

Lastly, we employ Definition 1 to show that Dynamic NEM satisfies the cost-causation principle.

Theorem 3 (Cost-causation conformity)**.** *Dynamic NEM satisfies the cost-causation principle.* □

IV. Numerical Results

To show the performance of the proposed mechanism, we assumed a hypothetical energy community of $H = 24$ households with flexible loads, while 19/24 of the households have rooftop solar. We used PecanStreet data[3], which has one year (2018) residential household data from Austin, TX.

To model consumption preferences of every $i \in \mathcal{H}$ household, we adopted the following quadratic concave utility:

$$U_{ik}(d_{ik}) = \begin{cases} \alpha_{ik} d_{ik} - \frac{1}{2}\beta_{ik} d_{ik}^2, & 0 \leq d_{ik} \leq \frac{\alpha_{ik}}{\beta_{ik}} \\ \frac{\alpha_{ik}^2}{2\beta_{ik}}, & d_{ik} > \frac{\alpha_{ik}}{\beta_{ik}} \end{cases}, \forall k \in \mathcal{K} \tag{14}$$

where α_{ik} and β_{ik} are utility parameters that are dynamically calibrated using the households' historical consumption, prices they face and their assumed elasticity[4] of consumption [5].

The community faces the utility's NEM X tariff with a time-of-use rate with $\pi_h^+ = \$0.40$/kWh and $\pi_l^+ = \$0.20$/kWh as peak and offpeak prices, respectively. For the export rate π^-, we used the average real-time wholesale prices[5] in Texas in 2018. Fixed charges were assumed to be zero, i.e., $\pi^0 = 0$.

[3]The data is accessible at Pecan St. Project.

[4]We assumed the households have homogeneous elasticity of -0.35.

[5]The data is accessible at: ERCOT.

Two energy communities are studied and compared: 1) a community under Dynamic NEM (referred to as *community 1*), and 2) a community under the allocation rule in [7] (referred to as *community 2*), with members performing consumption decisions similar to the optimal benchmark [15].

Fig.2 presents a summary of raw data. The left plot shows the daily average net consumption of each household (dashed blue) and their average (solid blue) in addition to the community's average net consumption (orange). During renewable generation hours, the average net consumption of many members has a different sign than the community's average net consumption, which gives them an additional benefit as shown by Dynamic NEM. The right plot shows the community's monthly aggregate renewable generation (green) and net consumption (red). The net consumption was much higher in summer signaling the high consumption in those months due to air-conditioning loads.

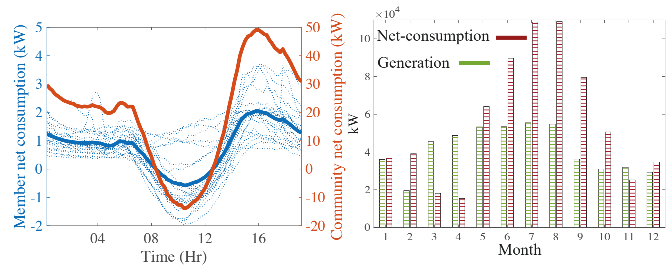

Fig. 2. Left: Individual and aggregate daily net consumption. Right: Aggregate monthly net consumption and renewable generation.

A. Community Members Surplus

Fig.3 shows the surplus (top) and payment (bottom) gains (%) after joining communities 1 and 2 over the benchmark of optimal customers under the utility's NEM X. Two NEM net billing periods were considered; 15-minutes (solid) and 1-hour (checked). Joining either community 1 or community 2 was advantageous for the households in terms of both surplus and payments. In all months, community 1 achieved higher surpluses and lower payments than community 2. Increasing the netting frequency from hourly to 15-min increased the value of joining the communities, as the benchmark customers become more vulnerable to the export rate. Lastly, the benefit of joining the energy community was the lowest when net consumption (Fig.2) was the highest, i.e., the period from June–September. This is because, in these months, community members, for most hours, face the same price their operator face at the PCC, which does not create benefits for them.

Fig.4 shows the surplus (top) and payment (bottom) gains (%) of DG adopters and non-adopters over their benchmark after joining community 1. Both classes benefited from joining the community by having higher surpluses and lower payments. However, adopters benefited more from the community as they more often operate in net consumption zones different than the community. Congruent with Fig.3, households benefited more from the community when the netting was faster.

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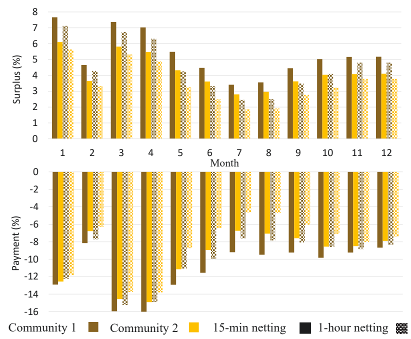

Fig. 3. Community monthly surplus and payment gains (%).

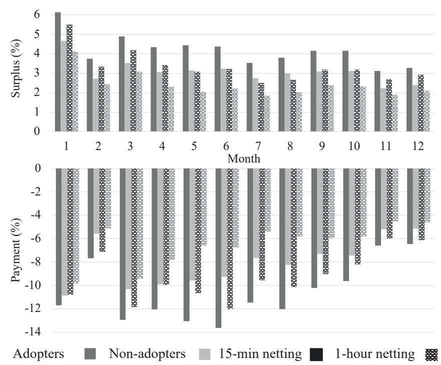

Fig. 4. Adopters/non-adopters monthly surplus and payment gains (%).

B. Reverse Power Flows

To grid operators, energy communities can relieve network congestion and reverse power flows (RPFs) that cause voltage instabilities [16]. The reduction of RPFs reduces the overall operating cost and enhances system reliability. Fig.5 shows the aggregate RPFs of a neighborhood of passive (top) and optimal – i.e., benchmark (middle) customers, and under community 1 (bottom) over three summer months. The benchmark customers (middle) resulted in lower RPFs than passive ones (top), as they dynamically increase their consumption to keep more of the renewables behind the utility revenue meter. The wiped-out aggregate RPFs heatmap of community 1 shows that the formation of the community diminished almost all RPF, due to sharing the renewable generation with other customers behind the PCC, which was further asserted by Dynamic NEM, which incentivized increasing the consumption when the community's renewable generation was abundant.

V. Conclusion

Energy communities overcome several physical, operational and financial challenges faced by standalone DER adoption. In this work, Dynamic NEM is proposed as a mechanism that decentrally achieves community welfare optimality through its surplus-maximizing members. In addition to satisfying the cost-causation principle, the community-resource-aware Dynamic NEM attains surplus levels for its members, that are not attainable under the utility's NEM regime outside the

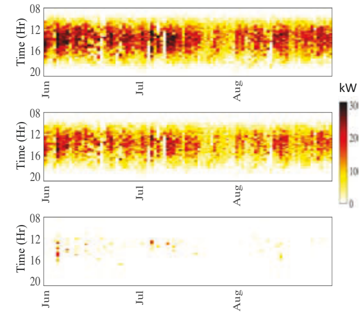

Fig. 5. Aggregate RPFs (in kW) of passive utility customers (top), active utility customers (middle), and energy community (bottom).

community. The structural properties of Dynamic NEM and its economical and operational intuitions are also highlighted.

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