Analysis of Billing Mechanisms for Equitable Energy Access in a Distributed Energy System

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Abstract

The increasing deployment of distributed energy resources (DER) has accelerated the transition toward clean and sustainable energy systems, while raising concerns about equitable energy access among heterogeneous consumers. In distributed energy systems (DES), the distribution of economic benefits is determined by pricing mechanisms such as Net Energy Metering (NEM) and Feed-in Tariff (FiT). While these mechanisms have been extensively studied for renewable energy integration and economic efficiency, their effects on surplus distribution and equity remain underexplored. To address this gap, this paper presents a systematic analytical framework to evaluate the surplus distribution and equity impacts of NEM and FiT in DES. The analysis explicitly links pricing mechanism design to individual consumer net benefits and equitable energy access. It assesses distributional outcomes using a Rawlsian equity criterion that prioritizes improvements for the least-advantaged participants. Case-wise comparative analysis is conducted to identify conditions under which NEM or FiT leads to more equitable outcomes, supported by numerical validation on a standard IEEE PES open dataset. The results highlight inherent trade-offs between efficiency and equity and provide analytical insights to support the design of pricing mechanisms that promote fair, affordable, and sustainable DES.

Keywords: Distributed Energy System, Energy Justice, Feed-in Tariff, Net Energy Metering, Rawlsian Equity.

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1. Introduction

The rapid growth of distributed energy resources (DERs), particularly rooftop photovoltaic generation, has played a key role in advancing the transition to clean, sustainable energy systems [1]. Pricing mechanisms such as Net Energy Metering (NEM) and Feed-in Tariff (FiT) are widely adopted to support this transition and have been shown to accelerate renewable deployment [2]. However, as distributed energy systems (DES) expand, growing evidence indicates that the distribution of economic benefits from these mechanisms is not shared equitably among consumers, raising concerns about equitable energy access [3, 4]. Most existing studies evaluate NEM and FiT using efficiency, adoption incentives and cost savings [5]. However, existing studies fail to examine how economic benefits are distributed across consumers, even though mechanisms that maximize total social welfare may still result in unequal distribution. As a result, the equity implications of pricing mechanisms remain inadequately examined, highlighting a significant gap. To address this gap, this paper adopts a Rawlsian equity framework, which prioritizes improvements for the least-advantaged participants, to systematically analyze and compare NEM and FiT mechanisms to promote equitable energy access in DES.

1.1. Related Work

Recent studies highlight the role of pricing mechanisms in integrating DES where past studies focused mostly on its implications for system efficiency degradation, renewable energy adoption and overall economic viability [2, 6]. The existing literature reveals that FiT schemes promote the use of renewable energies through guaranteed compensation and reduced investment risk [7, 8]. In contrast, NEM emerged as a widely adopted alternative that allows consumers to offset electricity consumption through self-generation, thereby encouraging prosumers' participation [9]. Subsequent studies compared NEM and FiT from a techno-economic and a regulatory view comparing their effect on the adoption incentives, utility revenues and costs at system-level [10]. These studies point out a number of challenges such as cross-subsidization [11] and cost shifting, particularly under NEM where non participating consumers may bear a disproportionately large share of network costs [12]. Notably, [13] stressed on the fact that adoption gaps coupled with racial, ethnic and income boundaries lead to inequitable energy affordability outcomes. Furthermore, several studies highlighted that unequal adoption of rooftop solar leads to inequity in the United States (U.S.) and other countries [14, 15]. While these studies provide important insights into the sustainability of tariffs and economic efficiency, they often do not discuss how the economic benefits are distributed across various consumer groups.

In parallel, an increasing body of research has documented ongoing inequality in electricity affordability and the energy burden. Reports from various sources, such as the 2017 American Housing Survey [16] and the U.S. Energy Information Administration (2022) [17], show that low-income households and consumers without access to distributed generation have a high energy burden and spend a larger percentage of income on electricity bills. These inequalities are further aggravated in DES, as the pricing structure is more favorable to consumers with generation assets, thereby affecting the affordability and energy access of non-participating consumers [18, 19]. Due to these inequalities, low-income consumers experience higher costs of energy, disproportionately carrying a higher energy burden, and also experiencing financial instability, which affects the quality of life & overall affordability [20]. To analyze these, various studies have used consumer surplus or net benefits as metrics to evaluate efficiency and welfare benefits in electricity pricing systems [21]. However, these surplus-based analyses are primarily used to assess total welfare and but do not systematically develop an analytical framework to evaluate equity under NEM and FiT pricing. Additionally, some prior work emphasized the need to rethink energy pricing from an equity perspective [22] and suggested structural and targeted policies, as well as financial aid to support low-income consumers [23, 24]. Despite extensive work, existing studies do not analyze or develop an analytical framework to examine the impact of current pricing on Social welfare and the equitable distribution of benefits, thereby highlighting a significant research gap. Furthermore, integrated techno-economic assessments of pricing policies that jointly consider equity and Social Welfare Function (SWF) remain underexplored.

This gap highlights the need to develop an analytical framework for comparative analysis of how existing NEM and FiT pricing mechanisms differ in their impacts on integrated social welfare and equity outcomes in DES. This paper addresses this gap by analytically comparing NEM and FiT using a Rawlsian equity criterion, which emphasizes outcomes for the least-advantaged participants, thereby providing a systematic assessment of integrated social welfare and equitable energy access in DES.

1.2. Summary of Contributions and Paper Organization

This work contributes to existing research by performing a comparative analysis of NEM and FiT pricing mechanisms with respect to overall social welfare and equity. The main contributions of this work are summarized as follows:

1. Analysis of Payment & Individual Surplus: This contribution contains a comparative analysis of consumer level payment & Individual surplus (net benefit after electricity consumption and bill payment) under both NEM and FiT mechanisms. The analysis examines the effect of pricing formulations on individual consumer net benefits and offers a structural analytical comparison to identify conditions in which one mechanism results in lower payments and higher net benefits than the other.

2. Equity Analysis: This work provides an analytical Rawlsian equity approach to evaluate the effect of pricing on the distribution of consumer surplus. It relates the payment structure to net-benefit inequality, allowing a comparative analysis of equity under both NEM & FiT mechanism.

3. Numerical Validation: The analytical results are verified through numerical evaluation using a standard IEEE PES open dataset, showing the consistency between the analytical conditions and the observed equity outcome under various pricing mechanisms.

This paper is organized as follows: Section II describes the Problem Formu-

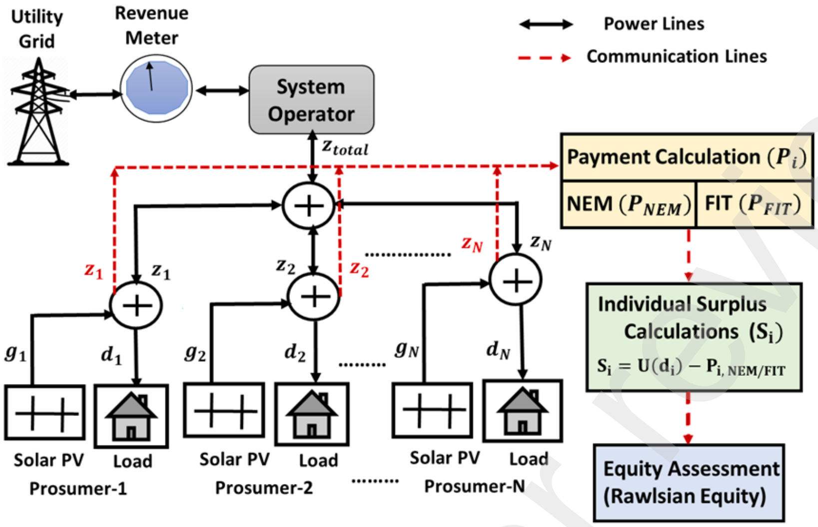

Figure 1: Schematic of the Distributed Energy System

lation, which includes the NEM and FiT pricing and the formulation of surplus. Section III discusses performance metrics for equity evaluation. Section IV provides a mathematical analysis and the main result. The numerical validation is presented in Section V. Finally, Section VI provides a concluding remark.

2. Problem Formulation

This section describes the schematic models of the DES: Subsection A describes FiT pricing formulation, Subsection B describes NEM pricing formulation, and Subsection C describes surplus and welfare formulations for further equity analysis.

Figure 1 illustrates the DES comprising N prosumers and presents the overall analytical framework for evaluating the equity implications of NEM and FiT pricing mechanisms. The physical layer consists of multiple prosumers (indexed by $i = 1, \ldots, N$), each characterized by electricity demand d_i and solar PV generation g_i [25]. The net energy consumption z_i of each consumer is calculated as shown in Eq. (2.1),

$$z_i = d_i - g_i \tag{2.1}$$

A positive z_i ($d_i > g_i$) indicates net energy consumption from the utility grid, while a negative z_i ($g_i > d_i$) indicates excess generation for export and the aggregate net energy consumption z_{total} of the DES is given in Eq. (2.2),

$$z_{\text{total}} = z_1 + z_2 + \cdots + z_N = \sum_{i=1}^{N} z_i \tag{2.2}$$

The Power flows between prosumers and the utility grid are shown by solid lines, while dashed lines represent information and settlement signals. Based on the measured net consumption z_i, the payment calculation module determines the consumer-level payment P_i using the NEM and FiT. These pricing formulations directly influence how exported and imported energy is valued. Using the resulting payment ($P_{i,\text{NEM,FiT}}$), the individual surplus (net benefit) (S_i) [26], for each consumer is computed as,

$$S_i = U_i(d_i) - P_{i,\text{NEM,FiT}} \tag{2.3}$$

where, $U_i(d_i)$ represents the utility derived from electricity consumption. The resulting individual surplus (S_i), obtained from utility function ($U_i(d_i)$) & the payment ($P_{i,\text{NEM, FiT}}$) is sent to the equity assessment module, where a Rawlsian equity-based evaluation is performed to analyze the equity across consumer under NEM & FiT pricing mechanism. This framework allows an analytical comparison of how different pricing mechanisms influence individual consumer surplus and overall equity.

The following subsection presents the payment and surplus formulations for NEM and FiT with details on how individual payments are computed as a function of demand di and renewable generation gi, which serve as the basis for subsequent equity analysis.

2.1. Feed-in Tariff

In the feed-in tariff mechanism, consumers pay for electricity demand at the import rate (π^+) and receive credits for their electricity generation at the export rate (π^-) [7, 8]. The net payment (P_i^{FiT}) for each prosumer i over a billing period is shown in Eq. (2.3):

$$P_i^{\mathrm{FiT}} = \pi^+ \cdot d_i - \pi^{\text{-}} \cdot g_i \tag{2.4}$$

where d_i and g_i are the electricity demand and generation, respectively.

2.2. Net Energy Metering

In this mechanism, the payment to each consumer i is determined based on the net energy difference $(d_i - g_i)$ for the billing period. If the energy demand (d_i) exceeds the energy generated (g_i), the consumer pays for the deficit $(d_i - g_i)$ at the import rate π^+. If the energy generated (g_i) exceeds consumption (d_i), the consumer is credited for the excess $(g_i - d_i)$ at the export rate π^- [9, 10]. The net payment (P_i^{NEM}) is calculated as shown in Eq. (2.5):

$$P_i^{\mathrm{NEM}} = \begin{cases} \pi^+ \cdot (d_i - g_i), & \text{if } d_i \geq g_i \quad \text{(net import)} \\ \pi^- \cdot (d_i - g_i), & \text{if } d_i < g_i \quad \text{(net export)} \end{cases} \tag{2.5}$$

With this calculation, the payment is directly based on the net energy difference $(d_i - g_i)$ during the billing period.

2.3. Individual Surplus and Social Welfare Formulation

For each consumer i, individual surplus (S_i) is the net benefit derived from energy consumption d_i, given in Eq. (2.6),

$$S_i(d_i, z_i) = \underbrace{U_i(d_i)}_{\text{utility of consumption}} - \underbrace{P_i(z_i)}_{\text{payment}} \tag{2.6}$$

where, $U_i(d_i)$ is the utility associated with energy consumption d_i, P_i is the payment, derived from a pricing mechanism (NEM or FiT). The optimal demand for each consumer i is subject to individual load and generation constraints and results in different consumption profiles [27]. The utility function $U_i(d_i)$ is modeled as shown in Eq. (2.7),

$$U_i(d_i) = c_i \cdot \log(d_i) \tag{2.7}$$

Here, c_i represents the consumer-specific utility factor, used to reflect heterogeneity in benefit perception across all consumers. This logarithmic utility function is widely adopted in energy economics to depict diminishing marginal utility, which represents the decreasing rate of consumer satisfaction, as the energy consumption d_i increases [27, 28]. The Social Welfare Function (SWF) [26, 27], of the total DES is obtained by aggregating the individual surpluses S_i for all consumers as shown in Eq. (2.8),

$$\text{SWF} = \sum_i S_i = \sum_i (U_i(d_i) - P_i) \tag{2.8}$$

Based on this formulation, the net surplus of each consumer (S_i) and the total SWF of the system can be quantified and compared directly under NEM and FiT.

3. Evaluation Metric

This section describes the metric used to assess each pricing mechanisms performance in reducing inequality to achieve a more equitable distribution of surplus benefits.

- Rawlsian Equity (RE): RE, which is based on John Rawls' definition of justice as fairness, focuses on fairness as measured by the comparison of the minimum individual surplus with the mean surplus of the rest of other consumers. This ratio emphasizes the relative position of the least advantaged consumer and ensures that increases in resource allocations pay much attention to their well-being. It is used as an index to measure equity in a distribution [27, 29, 30, 31]. The RE metric is expressed as shown in Eq. (3.2),

  $$RE^X = \frac{S^X_{\text{min}}}{S^X_{\text{mean}}} \tag{3.1}$$

  where: S^X_{min} is the minimum surplus under mechanism X, $S^X_{\text{mean}} = \frac{1}{N-1}\sum_{j \neq k_X} S^X_j$ is the mean surplus of rest others, for mechanism X, N is the total number of consumer, and k_X is the index of the minimum surplus under X. A higher RE value indicates a more equitable distribution, where the surplus of the least advantaged closely matches the mean surplus of others.

4. Mathematical Analysis and Main Results

This section presents the mathematical analysis and main results for NEM and FiT mechanism, individual surplus, and equity in surplus distribution, to assess their welfare and equity impacts within the system. For analytical comparison, it is assumed that consumption (d_i) remains the same under both NEM and FiT mechanisms.

4.1. Analytical Comparison of Payments Under NEM and FiT

This subsection compares the payments made by prosumer i under NEM and FiT using the formulations introduced earlier in section 2.

Theorem 1 (Payment Analysis: NEM vs FiT)**.** *For any prosumer i with demand d_i and generation g_i, and prices $\pi^+ \geq \pi^-$, the payment under FiT is greater than or equal to the payment under NEM:*

$$P_i^{\text{NEM}} \leq P_i^{\text{FiT}}, \tag{4.1}$$

with strict inequality whenever $d_i > 0$ and $\pi^+ \geq \pi^-$.

Proof. We consider all possible operating conditions.

Case 1: Net Consumption ($d_i > g_i$). Under NEM, the payment is

$$P_i^{\text{NEM}} = \pi^+(d_i - g_i) = \pi^+ d_i - \pi^+ g_i$$

Under FiT, the payment is

$$P_i^{\text{FiT}} = \pi^+ d_i - \pi^- g_i$$

The difference in payments is

$$\Delta P = P_i^{\text{NEM}} - P_i^{\text{FiT}}$$

$$\Delta P = (\pi^+ d_i - \pi^+ g_i) - (\pi^+ d_i - \pi^- g_i)$$

$$\Delta P = g_i(\pi^- - \pi^+) \tag{4.2}$$

Since $\pi^+ \geq \pi^-$ and $g_i \geq 0$, we have $\Delta P \leq 0$. Thus,

$$P_i^{\text{NEM}} \leq P_i^{\text{FiT}}.$$

Case 2: Net Export ($d_i < g_i$). Under NEM, the payment (negative indicates net credit) is

$$P_i^{\text{NEM}} = \pi^-(d_i - g_i) = \pi^- d_i - \pi^- g_i$$

Under FiT, the payment is

$$P_i^{\text{FiT}} = \pi^+ d_i - \pi^- g_i.$$

The payment difference is

$$\Delta P = P_i^{\text{NEM}} - P_i^{\text{FiT}}$$

$$\Delta P = (\pi^- d_i - \pi^- g_i) - (\pi^+ d_i - \pi^- g_i)$$

$$\Delta P = d_i(\pi^- - \pi^+) \tag{4.3}$$

Since $\pi^+ \geq \pi^-$ and $d_i \geq 0$, it follows that $\Delta P \leq 0$. Hence,

$$P_i^{\text{NEM}} \leq P_i^{\text{FiT}}.$$

Case 3: Exact Balance ($d_i = g_i$). Under NEM,

$$P_i^{\text{NEM}} = 0.$$

Under FiT,

$$P_i^{\text{FiT}} = \pi^+ d_i - \pi^- d_i = (\pi^+ - \pi^-) d_i \geq 0 \tag{4.4}$$

Therefore,

$$P_i^{\text{NEM}} \leq P_i^{\text{FiT}}$$

Thus, across all three operating conditions, the payment under NEM remains less than or equal to that under FiT. Hence, the inequality

$$P_i^{\text{NEM}} \leq P_i^{\text{FiT}}$$

holds for operating conditions, which concludes the proof.

4.2. Analytical Comparison of Surplus Under NEM and FiT

We already define the surplus $S_i = U_i(d_i) - P_i$, where the utility function is written as, $U_i(d_i) = c_i \log(d_i)$, which depends only on the consumption level d_i. Since the utility term $U_i(d_i)$ remains unchanged under NEM and FiT, any difference in consumer surplus arises solely from differences in the payment formulations.

Theorem 2 (Surplus Analysis: NEM vs FiT)**.** *Let $\pi^+ \geq \pi^-$ be the import and export prices, and let consumer i have demand d_i and generation g_i. Then,*

$$S_i^{\mathrm{NEM}} \geq S_i^{\mathrm{FiT}} \tag{4.5}$$

for all operating conditions, with strict inequality whenever $\pi^+ \geq \pi^-$ and $d_i > 0$.

Proof. We use the case-wise payment formulas and the definition $S_i^X = U_i(d_i) - P_i^X$.

Case 1: Net consumption ($d_i > g_i$). Under NEM, Surplus:

$$S_i^{\mathrm{NEM}} = U_i(d_i) - P_i^{\mathrm{NEM}} = U_i(d_i) - \pi^+ d_i + \pi^+ g_i$$

Surplus Under FiT:

$$S_i^{\mathrm{FiT}} = U_i(d_i) - P_i^{\mathrm{FiT}} = U_i(d_i) - \pi^+ d_i + \pi^- g_i$$

Difference:

$$\Delta S = S_i^{\mathrm{NEM}} - S_i^{\mathrm{FiT}}$$

$$\Delta S = \big(U_i(d_i) - \pi^+ d_i + \pi^+ g_i\big) - \big(U_i(d_i) - \pi^+ d_i + \pi^- g_i\big)$$

$$\Delta S = g_i(\pi^+ - \pi^-) \geq 0 \tag{4.6}$$

So $S_i^{\mathrm{NEM}} \geq S_i^{\mathrm{FiT}}$, strictly if $g_i > 0$ and $\pi^+ \geq \pi^-$.

Case 2: Net export ($d_i < g_i$). Under NEM, Surplus:

$$S_i^{\mathrm{NEM}} = U_i(d_i) - P_i^{\mathrm{NEM}} = U_i(d_i) - \pi^- d_i + \pi^- g_i$$

Under FiT, Surplus:

$$S_i^{\mathrm{FiT}} = U_i(d_i) - P_i^{\mathrm{FiT}} = U_i(d_i) - \pi^+ d_i + \pi^- g_i$$

Difference:

$$\Delta S = S_i^{\mathrm{NEM}} - S_i^{\mathrm{FiT}}$$

$$\Delta S = \big(U_i(d_i) - \pi^- d_i + \pi^- g_i\big) - \big(U_i(d_i) - \pi^+ d_i + \pi^- g_i\big)$$

$$\Delta S = d_i(\pi^+ - \pi^-) \geq 0 \tag{4.7}$$

So again $S_i^{\mathrm{NEM}} \geq S_i^{\mathrm{FiT}}$, strictly if $d_i > 0$ and $\pi^+ \geq \pi^-$.

Case 3: Exact balance ($d_i = g_i$). Under NEM, payment: $P_i^{\mathrm{NEM}} = 0$; therefore,

$$S_i^{\mathrm{NEM}} = c_i \log(d_i)$$

Under FiT, payment:

$$P_i^{\mathrm{FiT}} = \pi^+ d_i - \pi^- d_i = (\pi^+ - \pi^-)d_i,$$

and surplus:

$$S_i^{\mathrm{FiT}} = c_i \log(d_i) - (\pi^+ - \pi^-)d_i.$$

Difference:

$$\Delta S = S_i^{\mathrm{NEM}} - S_i^{\mathrm{FiT}}$$

$$\Delta S = c_i \log(d_i) - \big(c_i \log(d_i) - (\pi^+ - \pi^-)d_i\big)$$

$$\Delta S = (\pi^+ - \pi^-)d_i \geq 0 \tag{4.8}$$

Therefore,

$$S_i^{\mathrm{NEM}} \geq S_i^{\mathrm{FiT}}.$$

Thus, across all three operating conditions, the surplus under NEM is greater than or equal to that under FiT. Hence, the inequality

$$S_i^{\mathrm{NEM}} \geq S_i^{\mathrm{FiT}}$$

holds for all operating conditions, with strict inequality whenever $\pi^+ \geq \pi^-$, thereby completing the proof.

4.3. Analytical Comparison of Rawlsian Equity Under NEM and FiT

This subsection presents the Rawlsian Equity (RE) expressions under NEM and FiT and uses them to analyze the equity performance under the two mechanisms.

NEM:. For the net-import case ($d_i \geq g_i$)

$$\mathrm{RE}^{\mathrm{NEM}} = \frac{U_k - \pi^+(d_k - g_k)}{\frac{1}{N-1}\sum_{i\neq k}\left[U_i - \pi^+(d_i - g_i)\right]} \tag{4.9a}$$

$$= \frac{c_k \log(d_k) - \pi^+(d_k - g_k)}{\frac{1}{N-1}\sum_{i\neq k}\left[c_i \log(d_i) - \pi^+(d_i - g_i)\right]} = \frac{S^{\mathrm{NEM}}_{\mathrm{min}}}{S^{\mathrm{NEM}}_{\mathrm{mean}}} = \frac{A}{B}$$

For the net-export case ($d_i < g_i$)

$$\mathrm{RE}^{\mathrm{NEM}} = \frac{U_k - \pi^-(d_k - g_k)}{\frac{1}{N-1}\sum_{i\neq k}\left[U_i - \pi^-(d_i - g_i)\right]} \tag{4.9b}$$

$$= \frac{c_k \log(d_k) - \pi^-(d_k - g_k)}{\frac{1}{N-1}\sum_{i\neq k}\left[c_i \log(d_i) - \pi^-(d_i - g_i)\right]} = \frac{S^{\mathrm{NEM}}_{\mathrm{min}}}{S^{\mathrm{NEM}}_{\mathrm{mean}}} = \frac{A}{B}$$

where, k denotes the minimum-surplus consumer, with d_k and g_k denoting the minimum-surplus consumer's consumption and generation, and indices $i \neq k$ denote all the other consumers, with d_i and g_i denoting their respective consumption and generation. Here,

$$A = S^{\mathrm{NEM}}_{\mathrm{min}} = c_k \log(d_k) - \pi^{\pm}(d_k - g_k)$$

and

$$B = S^{\mathrm{NEM}}_{\mathrm{mean}} = \frac{1}{N-1}\sum_{i\neq k}\left[c_i \log(d_i) - \pi^{\pm}(d_i - g_i)\right]$$

denote the minimum surplus consumer and the average surplus of the rest of the other consumers in NEM and $\pi^{\pm}$ denotes the applicable NEM price defined in (2.2), i.e., π^+ for $d_i \geq g_i$ (net import) and π^- for $d_i < g_i$ (net export).

FiT:.

$$\mathrm{RE}^{\mathrm{FiT}} = \frac{U_k - \pi^+ d_k + \pi^- g_k}{\frac{1}{N-1}\sum_{i\neq k}\left[U_i - \pi^+ d_i + \pi^- g_i\right]} \tag{4.10}$$

$$= \frac{c_k \log(d_k) - \pi^+ d_k + \pi^- g_k}{\frac{1}{N-1}\sum_{i\neq k}\left[c_i \log(d_i) - \pi^+ d_i + \pi^- g_i\right]} = \frac{S^{\mathrm{FiT}}_{\mathrm{min}}}{S^{\mathrm{FiT}}_{\mathrm{mean}}} = \frac{C}{D}$$

where, similarly,

$$C = S_{\text{min}}^{\text{FiT}} = c_k \log(d_k) - \pi^+ d_k + \pi^- g_k$$

and

$$D = S_{\text{mean}}^{\text{FiT}} = \frac{1}{N-1} \sum_{i \neq k} \left[c_i \log(d_i) - \pi^+ d_i + \pi^- g_i \right]$$

represent the minimum surplus consumer and the average surplus of the rest of the other consumers in FiT.

To make FiT more equitable than NEM require,

$$\text{RE}^{\text{FiT}} > \text{RE}^{\text{NEM}} \quad \iff \quad \frac{C}{D} > \frac{A}{B} \iff (\frac{S_{\text{min}}^{\text{FiT}}}{S_{\text{mean}}^{\text{FiT}}}) > (\frac{S_{\text{min}}^{\text{NEM}}}{S_{\text{mean}}^{\text{NEM}}}) \tag{4.11}$$

Equivalently,

$$C\,B > A\,D \iff (S_{\text{min}}^{\text{FiT}})\,(S_{\text{mean}}^{\text{NEM}}) > (S_{\text{min}}^{\text{NEM}})\,(S_{\text{mean}}^{\text{FiT}}) \tag{4.12}$$

- If $C\,B > A\,D \Rightarrow$ FiT is more equitable than NEM.
- If $C\,B < A\,D \Rightarrow$ NEM is more equitable than FiT.
- If $C\,B = A\,D \Rightarrow$ both mechanisms have the same Rawlsian equity.

4.3.1. Rawlsian Equity Analysis: NEM vs FiT

Case 1: Net-Consumption. ($d_k > g_k$ & $d_{\text{avg}} > g_{\text{avg}}$)

Rawlsian equity under NEM is written as,

$$\text{RE}^{\text{NEM}} = \frac{U_k - \pi^+(d_k - g_k)}{\frac{1}{N-1}\sum_{i \neq k}\left[U_i - \pi^+(d_i - g_i)\right]}$$

Define the averages over all consumers except k, for simplification,

$$U_{\text{avg}} = \frac{1}{N-1} \sum_{i \neq k} U_i$$

$$d_{\text{avg}} = \frac{1}{N-1} \sum_{i \neq k} d_i, \quad g_{\text{avg}} = \frac{1}{N-1} \sum_{i \neq k} g_i,$$

Using these averages, the above NEM equity expression can be written as,

$$\text{RE}^{\text{NEM}} = \frac{U_k - \pi^+ d_k + \pi^+ g_k}{U_{\text{avg}} - \pi^+ d_{\text{avg}} + \pi^+ g_{\text{avg}}} \tag{4.13}$$

Introduce short notations for the common terms in the consumption components of surplus,

$$M := U_k - \pi^+ d_k, \qquad \hat{M} := U_{\text{avg}} - \pi^+ d_{\text{avg}}$$

Then,

$$\text{RE}^{\text{NEM}} = \frac{M + \pi^+ g_k}{\hat{M} + \pi^+ g_{\text{avg}}} = \frac{A}{B} \tag{4.14}$$

Similarly, Rawlsian Equity under FiT is,

$$\text{RE}^{\text{FiT}} = \frac{U_k - \pi^+ d_k + \pi^- g_k}{U_{\text{avg}} - \pi^+ d_{\text{avg}} + \pi^- g_{\text{avg}}} = \frac{M + \pi^- g_k}{\hat{M} + \pi^- g_{\text{avg}}} = \frac{C}{D} \tag{4.15}$$

Theorem 3 (Rawlsian Equity Ordering)**.** *Assume that $\pi^+ \geq \pi^-$ and $g_{\text{avg}} \geq g_k$. Then FiT yields higher Rawlsian Equity than NEM if and only if,*

$$M\, g_{\text{avg}} \;>\; \hat{M}\, g_k$$

Proof. The condition that FiT is more equitable than NEM ($CB > AD$) is therefore,

$$\frac{M + \pi^- g_k}{\hat{M} + \pi^- g_{\text{avg}}} > \frac{M + \pi^+ g_k}{\hat{M} + \pi^+ g_{\text{avg}}} \tag{4.16}$$

Cross–multiplying the two fractions yields,

$$(M + \pi^- g_k)(\hat{M} + \pi^+ g_{\text{avg}}) > (M + \pi^+ g_k)(\hat{M} + \pi^- g_{\text{avg}})$$

Expanding both sides and cancelling common terms in $M\hat{M}$ gives,

$$M\, \pi^+\, g_{\text{avg}} + \hat{M}\, \pi^-\, g_k > M\, \pi^-\, g_{\text{avg}} + \hat{M}\, \pi^+\, g_k$$

Rearranging the inequality to group M–terms on the left and $\hat{M}$–terms on the right gives,

$$M\, g_{\text{avg}}\, (\pi^+ - \pi^-) > \hat{M}\, g_k\, (\pi^+ - \pi^-) \tag{4.17}$$

Since the import rate exceeds the export rate ($\pi^+ \geq \pi^-$), we can divide by the positive factor ($\pi^+ - \pi^-$) and obtain the final condition, which results in FiT yields a more Rawlsian equitable distribution of surplus in Case 1 is,

$$M\, g_{\text{avg}} > \hat{M}\, g_k \tag{4.18}$$

4.4. Interpretation of the Equity Condition

The derived condition for FiT to improve Rawlsian equity is,

$$M\, g_{\text{avg}} > \hat{M}\, g_k \tag{4.18}$$

where, the terms M and $\hat{M}$ denote the net utility of the worst-off consumer and the average net utility of the remaining consumers, respectively, while g_k and g_{avg} denote the corresponding generation levels of the minimum-surplus consumer and the average generation of the rest of the other consumers. To interpret this condition, first note that the ordering $g_{\text{avg}} > g_k$ holds by construction. The worst-off consumer k is defined as the one with the minimum surplus, and surplus is increasing in generation under both NEM and FiT. Hence, a consumer with a higher generation cannot be the worst off when another consumer has a lower generation. The worst-off consumer must therefore have the minimum generation level, i.e., $g_k = \min_i g_i$. By definition of an average, the mean generation of the remaining consumers therefore satisfies $g_{\text{avg}} \geq g_k$, with strict inequality in non-degenerate systems. The key question is thus whether differences in generation are sufficiently larger than differences in net utility.

This condition indicates that FiT enhances Rawlsian equity when the relative difference in generation levels across consumers exceeds the variation in their net utility levels, leading to the dominance of the term $M\, g_{\text{avg}} > \hat{M}\, g_k$. This situation is common in DES where generation assets like rooftop photovoltaic systems are unevenly distributed among consumers because of capital constraints, housing characteristics, access to incentives, etc., resulting in large variations in generation levels. In contrast, differences in consumption-based utility are mitigated by the concavity of the utility function, significant variations in consumption level lead to relatively smaller variations in net utility across consumers, making the distribution less dispersed. As a result, consumer generation levels typically exhibit greater variation than their corresponding net utility levels. Consequently, the product term ($M\, g_{\text{avg}}$) is likely to be larger than ($\hat{M}\, g_k$), suggesting that the derived condition is expected to hold in many practical distributed energy systems.

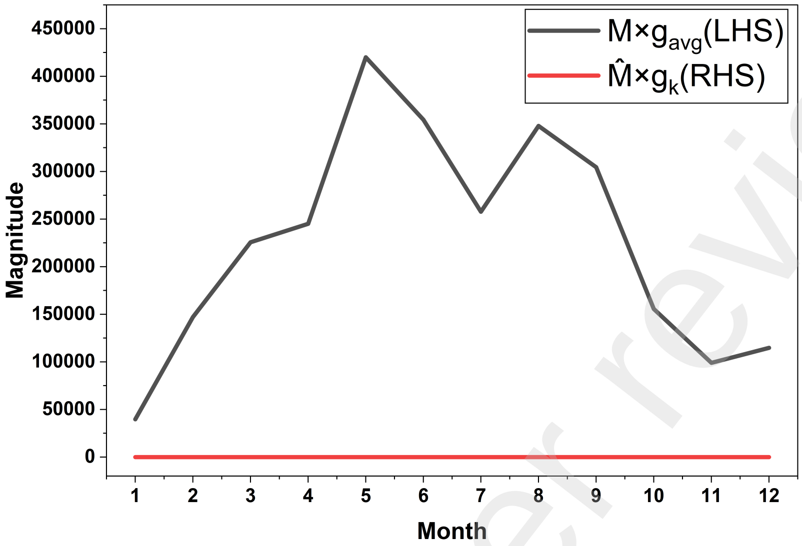

Figure 2: Monthly comparison of the analytical terms ($M\,g_{\text{avg}}$) and ($\hat{M}\,g_k$)

This interpretation is supported by the empirical results shown in Fig. 2, which compare the two analytical terms ($M\,g_{\text{avg}}$) and ($\hat{M}\,g_k$), over the twelve-month period. In the dataset considered, the minimum-surplus consumer does not have distributed generation, resulting in $g_k = 0$. As a result, the term ($\hat{M}\,g_k$) remains zero, while the term ($M\,g_{\text{avg}}$) varies according to the monthly generation levels of the remaining consumers and remains strictly positive throughout the year. As shown in figure 2, the term ($M\,g_{\text{avg}}$) consistently dominates the term ($\hat{M}\,g_k$) in all the months indicating that the derived condition $M\,g_{\text{avg}} > \hat{M}\,g_k$ holds for the entire time period covered in the study.

Furthermore, even in scenarios where the minimum-surplus consumer has a small amount of generation ($g_k > 0$), the structural ordering $g_{\text{avg}} \geq g_k$, typically holds in DES due to heterogeneous generation ownership. Since the variation in net utility levels remains relatively limited, while generation levels can differ substantially across consumers, the product term ($M\,g_{\text{avg}}$) still exceeds ($\hat{M}\,g_k$). This observation provides strong empirical support for the derived condition and explains why the FiT mechanism consistently yields higher Rawlsian equity than

NEM in the numerical results, as shown in Table 4 below.

4.5. Discussion of Other Operating Cases

The Rawlsian equity result above relies on a structural feature of the net-consumption case-1 ($d_k > g_k$, & $d_{\text{avg}} > g_{\text{avg}}$): the worst-off consumer must also have the minimum generation level, which implies $g_{\text{avg}} > g_k$. This property makes the equity comparison between NEM and FiT in Case-1 clear and tractable. In other operating conditions, however, this structural ordering does not generally hold. In the net-export case-2 ($d_k < g_k$ & $d_{\text{avg}} < g_{\text{avg}}$), the equity comparison involves consumption rather than generation, leading to conditions such as,

$$M\, d_{\text{avg}} > \hat{M}\, d_k \tag{4.19}$$

where,

$$M := U_k + \pi^- g_k, \qquad \hat{M} := U_{\text{avg}} + \pi^- g_{\text{avg}} \tag{4.20}$$

and it depends on utility and generation. Unlike generation, consumption does not admit a monotone ordering with respect to surplus, so the worst-off consumer need not have the lowest or highest consumption level. Therefore, no general inequality between d_{avg} and d_k can be derived without extra assumptions. As a result, the equity ordering between NEM and FiT in these other cases becomes data-dependent and cannot be expressed in a simple analytical form.

5. Numerical Validation

This section presents the numerical validation of the payment, surplus, and equity analysis under the NEM and FiT pricing mechanisms, as discussed in earlier sections.

The numerical validation is conducted using the IEEE PES Open Dataset, which comprises electricity consumption and Solar PV generation profiles for 15 prosumers at 15-minute resolution over the full year of 2019. The study period covers the entire year of 2019, and the billing period is one month [32]. The

15-minute resolution time-series data is aggregated into monthly energy values to compute the payment using the NEM & FiT mechanism, as shown in Table 1. Each consumer's utility is expressed as a logarithmic function of demand (d_i). Based upon these formulations, individual surplus for each member is computed using the corresponding utility & payment obtained under the NEM and FiT pricing mechanism. These surplus values are then used to further calculate the Rawlsian equity metric, which is used for comparative equity analysis.

Table 1: Community Monthly Total Consumption and Generation

Month	(a)	(b)	(a)–(b)
1	9 675.45	2 889.70	6 787.75
2	8 387.95	3 450.77	4 937.18
3	9 220.98	5 276.72	3 944.25
4	8 558.83	5 049.03	3 509.79
5	8 607.93	6 541.01	2 066.92
6	8 239.93	5 665.33	2 574.60
7	8 727.03	6 043.65	2 683.38
8	7 651.57	6 193.44	1 458.13
9	8 191.39	5 121.49	3 069.90
10	9 206.38	3 342.20	5 864.18
11	8 991.04	1 796.34	7 194.69
12	9 631.67	1 947.33	7 684.35
Total	105 090.14	53 317.02	51 773.12

(a) Energy consumption (kWh) (b) Energy generation (kWh)

Figure 3 shows the daily load profiles for two representative days (01/01/2019 and 02/01/2019) used in case study. The shaded area measures the value of the aggregated demand of all consumers at each time periods, and the solid line is the corresponding average demand per consumer. The profile reflects the typical variation in electricity consumption over a day, with reduced demand

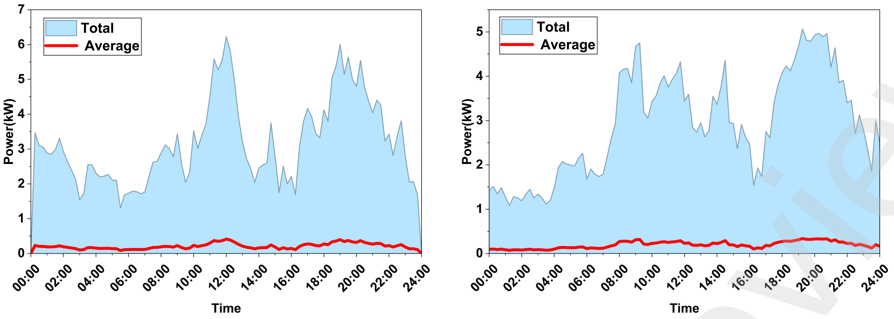

Figure 3: Daily demand profiles (total and average load per consumer): (a) left—01/01/2019; (b) right—02/01/2019.

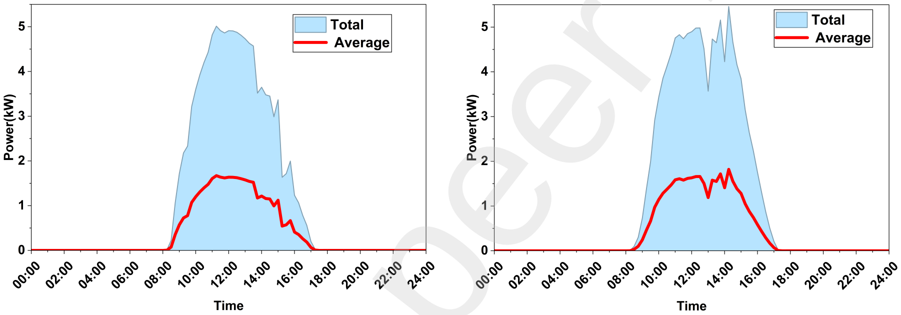

Figure 4: Daily solar PV generation (total and average generation): (a) left—01/01/2019; (b) right—02/01/2019.

during the early hours of the day and increasing demand towards mid-day with higher demands observed during evening periods. The variation in peak levels and overall shape between the two days indicates the day to day variation within the natural load pattern considered in the analysis.

Following the daily demand patterns shown in Figure 3, Figure 4 shows the daily solar PV generation for the same representative days. The shaded region indicates the total aggregated PV output of the prosumers, and the solid line represents the average generation. As observed, PV generation occurs only during daylight hours, rising after sunrise, reaching its maximum around midday, and decreasing toward evening. The differences in peak level and profile shape

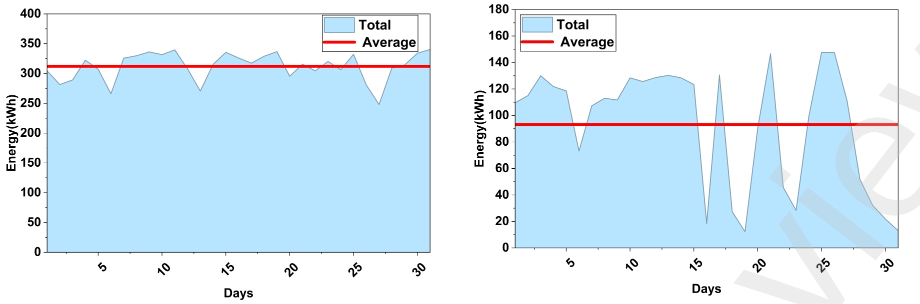

Figure 5: Daily total energy consumption (left) and PV generation (right) in January 2019 with the corresponding monthly average.

between the two days capture the typical intermittency of solar PV generation. These generation profiles, combined with the corresponding load data, are used to calculate net energy consumption and form the basis for subsequent payment, surplus, and equity analysis.

Figure 5 shows the aggregated total energy consumption and solar PV generation for January 2019, which illustrates the variation within the month. The daily consumption is comparatively steady with moderate fluctuations while PV generation is more variable from day to day due to changing solar conditions. A few days have generation levels that are noticeably higher or lower due to the inherent natural variability of the resources. These monthly trends are used in further payment and equity analysis.

5.1. Results

This subsection shows the numerical results of the payment, surplus, and equity analysis under the NEM & FiT mechanism. The corresponding results are shown in the following tables to facilitate the comparative analysis under both NEM & FiT mechanisms. The payment results shown in Table 2 are align with the previous analytical comparison, which showed that payments under FiT are greater than or equals to those under NEM across all operating cases. The numerical results confirm that NEM leads to reduced monthly payments, but the amount by which NEM reduce payments varies from month to month. This

Table 2: Monthly Payment Savings Under NEM Compared to FiT

Month	(a)	(b)	(c)	(d)
1	2 613.66	2 035.72	577.94	22.11
2	2 171.31	1 481.15	690.15	31.78
3	2 239.48	1 184.14	1 055.34	47.12
4	2 061.88	1 052.07	1 009.80	48.97
5	1 928.27	620.07	1 308.20	67.84
6	1 905.44	772.37	1 133.06	59.46
7	2 013.74	805.01	1 208.73	60.02
8	1 676.94	438.26	1 238.68	73.86
9	1 945.26	920.96	1 024.29	52.65
10	2 427.69	1 759.25	668.44	27.53
11	2 517.67	2 158.40	359.26	14.26
12	2 694.76	2 305.30	389.46	14.45
Total	26 196.16	15 532.76	10 663.40	40.70

(a) FiT payment (\$) (b) NEM payment (\$)

(c) Payment savings ($c = a - b$) (\$) (d) Percentage savings ($d = c/a$) (%)

variation follows the demand generation balance shown in Table 1. In months where distributed generation makes a greater contribution to total consumption, it shows higher levels of payment savings under NEM than FiT as seen for months such as 5 & 8. In contrast, if generation is relatively low, the difference between the two mechanisms will be less pronounced, as seen in months 11 & 12. The annual totals in Table 2 show that NEM results in much lower payments than FiT and it results in an overall saving of about 40.70%. These findings indicate that the relative economic benefit of NEM depends on the profile of monthly demand generation, which influences individual surplus and equity outcomes.

The surplus results shown in Table 3 are align with the analytical condition of Theorem 2 and the previous payment comparison. The analysis indicate that

Table 3: Monthly Surplus Benefits under NEM Relative to FiT

Month	(a)	(b)	(c)	(d)
1	5 464.89	4 886.95	577.94	10.58
2	5 859.99	5 169.83	690.15	11.78
3	6 265.01	5 209.66	1 055.34	16.85
4	6 296.18	5 286.37	1 009.81	16.04
5	6 730.11	5 421.91	1 308.20	19.44
6	6 499.23	5 366.17	1 133.07	17.43
7	6 555.24	5 346.51	1 208.73	18.44
8	6 747.43	5 508.74	1 238.69	18.36
9	6 379.53	5 355.23	1 024.30	16.06
10	5 629.87	4 961.43	668.44	11.87
11	5 282.01	4 922.74	359.27	6.80
12	5 267.82	4 878.36	389.47	7.39
Overall SWF	72 977.29	62 313.89	10 663.40	14.61

(a) Surplus under NEM (b) Surplus under FiT

(c) Surplus benefits $c = a - b$ (d) Percentage benefits $d = c/a$ (%)

individual consumer surplus under NEM is higher than or equal those under FiT, for all operating case, as observed in the numerical results across all months. The amount of surplus improvement changes over time and is consistent with the demand generation balance summarized in Table 1. Months with relatively higher distributed generation, which showed larger payment reductions under NEM (Table 2), also exhibit greater surplus gains, as observed in months such as 5 & 8. In contracts, when generation is lower relative to consumption, the surplus gap between the two mechanisms becomes less pronounced, as observed in months such as 11 & 12. As a result, the overall SWF is higher under NEM than FiT, reflecting higher monthly surplus observed under NEM. The annual totals reported in Table 3 show that NEM provides higher consumer surplus than FiT across the year, with an overall surplus improvement of about 14.61%.

These findings suggest that the analytical surplus comparison is supported by numerical validation and that differences in payments directly translate into variations in consumer surplus, forming the basis for the subsequent equity analysis.

Table 4: Monthly Rawlsian equity and analytical terms ($M\,g_{\text{avg}}$) and ($\hat{M}\,g_k$)

Month	(a)	(b)	(c)	(d)	(e)	(f)
1	0.106	0.119	11.85	39 654	0	39 654
2	0.313	0.355	13.61	147 090	0	147 090
3	0.293	0.353	20.66	225 649	0	225 649
4	0.331	0.397	19.70	245 095	0	245 095
5	0.373	0.465	24.86	420 033	0	420 033
6	0.416	0.507	21.88	354 365	0	354 365
7	0.278	0.343	23.16	257 721	0	257 721
8	0.359	0.442	23.19	347 913	0	347 913
9	0.403	0.482	19.78	304 523	0	304 523
10	0.356	0.406	13.86	155 589	0	155 589
11	0.452	0.487	7.55	98 996	0	98 996
12	0.486	0.527	8.28	114 793	0	114 793

(a) RE^{NEM} (b) RE^{FiT} (c) Equity gain, ($c = b - a/a$) (%)
(d) ($M\,g_{\text{avg}}$) (e) ($\hat{M}\,g_k$) (f) Difference, ($f = d - e$)

Table 4 presents the monthly Rawlsian equity indices under NEM and FiT, along with the corresponding equity gains and the relative disparity in generation levels and the variation in their net utility level. A higher Rawlsian equity index means that the minimum surplus is closer to the average surplus of the other consumers, indicating improved distribution sensitive performance. The results demonstrate that Rawlsian equity under FiT is more than under NEM in every month leading to a positive equity gain over the entire study period. Moreover, the analytical term ($M\,g_{\text{avg}}$) is substantially higher than ($\hat{M}\,g_k$) throughout the dataset, stating that the derived condition holds in all observed scenarios. This numerical evidence is consistent with the theoretical result and explains the increased Rawlsian equity observed under the FiT mechanism. The variation in equity gain follows the analytical pattern, as illustrated in Figure 2. In particular, months 5, 7, and 8 show relatively higher values ($M\, g_{\text{avg}}$) compared to ($\hat{M}\, g_k$), resulting in a higher equity gain under the FiT mechanism. In contrast, for months 11 and 12, although the value of ($M\, g_{\text{avg}}$) remains relatively high, but, the percentage equity gain is lower. This is because the gain also depends upon the baseline Rawlsian equity under NEM, as reported in Table 4.

In summary, the numerical results satisfy the analytical condition $M\, g_{\text{avg}} > \hat{M}\, g_k$ across all months considered in the dataset. The empirical evaluation therefore supports the theoretical result that the FiT mechanism leads to higher Rawlsian equity than NEM. Overall, the numerical results consistent with the analytical findings and validate the derived equity condition.

6. Conclusion and Future Work

This work provides a structured analytical framework for NEM and FiT pricing mechanisms, with emphasis on individual surplus (net benefits) and Rawlsian equity outcomes, in DES. The analytical results indicate that the payments under NEM are less than or equal to those under FiT across all operating cases. Consequently, the surplus analysis shows that consumer surplus under NEM is greater than or equal to that under FiT. These analytical results are supported by numerical validation using a standard IEEE PES open dataset, confirming the analytical results with the numerical observations. Beyond economic performance, the study evaluates the distribution of benefits using a Rawlsian equity index to assess how individual surplus is distributed across consumers. The case-wise equity analysis indicates that FiT consistently achieves higher Rawlsian equity values than NEM, indicating a more equitable surplus distribution. The variation observed in equity outcomes is linked to the relative magnitude of analytical term ($M\, g_{\text{avg}}$) and ($\hat{M}\, g_k$). The numerical results confirm that $M\, g_{\text{avg}} > \hat{M}\, g_k$ holds across the dataset. In particular, this condition is satisfied in the net-consumption case ($d_i > g_i$), which represents the most common operating case observed in practical DES, indicating that FiT is likely to provide higher Rawlsian equity than NEM.

Overall, the results suggest that the design of the pricing mechanism has implications for both economic efficiency as well as distribution of benefits to consumers, hence affecting equitable energy access. These findings highlight the importance of integrating an equity-aware assessment framework into distributed energy pricing to ensure equitable distribution of benefits and promote sustainable development goals.

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