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Optimal Solar Investment and Operation under Asymmetric Net Metering

Nathan Engelman Lado†, Ahmed S. Alahmed‡, Audun Botterud†, Saurabh Amin†

***Abstract*—We examine the joint investment and operational decisions of a *prosumer*, a customer who both consumes and generates electricity, under net energy metering (NEM) tariffs. Traditional NEM schemes provide temporally flat compensation at the retail price for net energy exports over a billing period. However, ongoing reforms in several U.S. states are introducing time-varying prices and asymmetric import/export compensation to better align incentives with grid costs. While prior studies treat PV capacity as exogenous and focus primarily on consumption behavior, this work endogenizes PV investment and derives the marginal value of solar capacity for a flexible prosumer under asymmetric NEM tariffs. We characterize optimal investment and show how optimal investment changes with prices and PV costs. Through this analysis, we identify a PV effect: changes in NEM pricing in one period can influence net demand and consumption in generating periods with unchanged prices through adjustments in optimal PV investment. The PV effect weakens the ability of higher import prices to increase prosumer payments, with direct implications for NEM reform. We validate our theoretical results in a case study using simulated household and tariff data derived from historical conditions in Massachusetts.**

***Index Terms*—Demand response, distributed energy resources, flexible demand, net metering, prosumer, sizing, solar PV.**

I. Introduction

The rapid deployment of behind-the-meter distributed energy resources (DERs), particularly rooftop photovoltaic (PV) systems and flexible loads, is transforming electricity consumption and generation patterns at the distribution level. Customers equipped with such resources, commonly termed prosumers, are able to both import electricity from and export surplus generation to the distribution utility (DU) [1]. Net energy metering (NEM) has emerged as the predominant tariff mechanism for facilitating bidirectional energy exchange in the United States. Under conventional NEM, a customer's net energy consumption is calculated over a billing period. Net imports are charged at the prevailing retail price and net exports are compensated with credits, typically valued at the retail rate (symmetric NEM) or at a reduced price (asymmetric NEM) [2].[1]

Although many existing NEM tariffs remain time-invariant and symmetric, a growing number of jurisdictions are transitioning toward time-varying and asymmetric import/export tariff structures. These reforms aim to better reflect marginal system costs, improve grid efficiency, and align prosumer incentives with distribution system needs [3], [4]. Notable examples of asymmetric NEM tariffs include those recently adopted in California, Arizona, Georgia, Michigan, and Illinois [5]. Utilities advocate for such reforms on the grounds that symmetric NEM shifts fixed network costs onto non-solar customers [2], while solar industry stakeholders argue that reduced export compensation stalls adoption [3]. Understanding how these tariff structures affect prosumer investment decisions is therefore of direct practical importance.

Much of the existing literature on NEM examines either operational DER decisions under fixed capacity or DER adoption in aggregate. Early work studies prosumer behavior, benefits, and PV adoption under legacy NEM tariffs with symmetric prices [6]–[9]. Within this literature, operational analyses often treat PV capacity as exogenous and focus on how prosumers schedule consumption and DER operation given a fixed level of installed capacity.

More recent studies consider operational decisions and DER aggregation under time-varying and asymmetric NEM tariffs [10], [11], but generally maintain the assumption of exogenous PV capacity. Other work endogenizes PV capacity under NEM without incorporating demand flexibility [12]–[14]. In contrast, our work endogenizes PV capacity, incorporates prosumer flexibility, and analyzes asymmetric, time-varying NEM tariffs. We show that jointly optimizing investment and operational decisions exposes effects that are not captured when PV capacity is treated as fixed.

Summary of Contributions: This paper studies the joint investment and operational decisions of a prosumer with behind-the-meter PV generation and flexible loads under general NEM tariffs. More specifically:

- We demonstrate that optimal PV capacity depends on a weighted average of prices and marginal utilities derived from the import, export, and net-zero (self-consumption) regimes. We then derive comparative statics with respect to changes in import/export prices and solar cost.
- We identify the PV effect: when NEM prices change in one period, adjustments to optimal solar capacity affect prosumer consumption, net demand, and payments in all other generation periods.
- We show that net-zero self-consumption periods dampen the sensitivity of PV investment to price and cost changes, smoothing capacity responses relative to regimes valued at market prices.
- We present a numerical case study using simulated Massachusetts demand and renewable generation. The case study demonstrates why this work is relevant to regulators and utilities by illustrating how NEM tariffs affect prosumer investment, net demand, consumption, and cost recovery.

Paper Notations and Organization: A summary of notations used in the paper is provided in Table I. The rest of the

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[1]Symmetric and asymmetric NEM designs are also referred to in the literature as full NEM and partial NEM, respectively.

TABLE I: Notation summary

Sets			
$\mathcal{T}$	Periods	$\mathcal{T}^g \subseteq \mathcal{T}$	Gen. Periods
Parameters			
$c^g \in \mathbb{R}_{\geq 0}$	Cost of PV inv.	$\pi_t^+ \in \mathbb{R}_{\geq 0}$	Import price
$\psi_t \in \mathbb{R}_{\geq 0}$	Cap. factor	$\pi_t^- \in \mathbb{R}$	Export price
$\bar{\psi}_t \in \mathbb{R}_{\geq 0}$	Cap. factor bnd.	$\pi^c \in \mathbb{R}$	Fixed charge
$\bar{g} \in \mathbb{R}_{\geq 0}$	PV cap. bnd.	$U_t(\cdot) \in \mathbb{R}$	Period-t utility
Decision Variables			
$d_t \in \mathbb{R}_{\geq 0}$	Electricity cons.	$d_t^+ \in \mathbb{R}_{\geq 0}$	Import
$g \in \mathbb{R}_{\geq 0}$	Solar cap.	$d_t^- \in \mathbb{R}_{\geq 0}$	Export
Auxiliary Quantities			
$P^{\text{NEM}} \in \mathbb{R}$	NEM payment	$\bar{d}_t^\pm \in \mathbb{R}_{\geq 0}$	Imp./Exp. thresh.
$\underline{d}^+ \in \mathbb{R}_{\geq 0}$	PV Threshold	$S \in \mathbb{R}$	Prosumer Surplus
Dual Variables			
$\gamma_t \in \mathbb{R}$	Balance constr. dual	$\alpha_t \in \mathbb{R}_{\geq 0}$	Imp. nonneg. dual
$\beta_t \in \mathbb{R}_{\geq 0}$	Exp. nonneg. dual	$\kappa \in \mathbb{R}_{\geq 0}$	PV nonneg. dual
$\rho \in \mathbb{R}_{\geq 0}$	PV cap. constr. dual		

paper is organized as follows. Sec. II presents the prosumer payment and decision model under a general NEM tariff structure. Sec. III delineates the optimal operation and investment decisions of a prosumer under NEM. Sec. IV presents a case study for a prosumer under NEM using simulated data for a household in Massachusetts, followed by concluding remarks in Sec. V. Mathematical proofs of the theoretical results and explanations of parameter choices for the case study are presented in the appendix.

II. Prosumer Decisions Model and Payment

DER and Payment under NEM: We consider a prosumer facing a finite set of settlement periods $t \in \mathcal{T}$. A prosumer consumes electricity, d_t, and generates electricity in each period, $\psi_t g$. For the set of generating periods, $\mathcal{T}^g$, the capacity factor is a continuously distributed parameter $\psi_t \in [0, \bar{\psi}_t]$. For periods $t \in \mathcal{T} \setminus \mathcal{T}^g$, the capacity factor is zero, *i.e.*, $\bar{\psi}_t = 0$.

Energy balance requires that net demand equals the difference between imports and exports, hence,

$$d_t - \psi_t g = d_t^+ - d_t^-.$$

The prosumer's net demand in period t, $d_t^+ - d_t^-$, is positive if consumption exceeds generation ($d_t > \psi_t g$), negative if generation exceeds consumption ($d_t < \psi_t g$), and zero if they are equal ($d_t = \psi_t g$). Using the import and export variables, the total payment under NEM[2] is defined as follows

$$P^{\text{NEM}} := \pi^c + \sum_{t \in \mathcal{T}} \Big(\pi_t^+ d_t^+ - \pi_t^- d_t^- \Big). \tag{1}$$

The expected payment is $\mathbb{E}[P^{\text{NEM}}]$, with expectation taken over ψ_t. We assume that the import price is greater than the export price, $\pi_t^+ > \pi_t^-$, and treat the case of equal prices by subtracting a small offset from π_t^-.

Prosumer Decision Problem: The consumer derives utility $U_t(d_t)$ from electricity consumption. We assume the utility function is increasing, twice-differentiable, and strictly concave. Following standard microeconomics literature, the prosumer's problem is modeled as a surplus maximization problem [15], where surplus is the difference between the utility of consuming electricity and incurred charges due to consumption and investment decisions:

$$S^* = \max_{\substack{d_t^+, d_t^- \\ g, d_t}} \sum_{t \in \mathcal{T}} \mathbb{E}\Big[U_t(d_t) - \pi_t^+ d_t^+ + \pi_t^- d_t^-\Big] - c^g g - \pi^c \tag{2a}$$

$$\text{s.t.} \quad d_t^+ - d_t^- = d_t - g\psi_t \ : \ \gamma_t \qquad \forall t \in \mathcal{T} \tag{2b}$$

$$g \geq 0, g \leq \bar{g} \qquad : \kappa, \rho \tag{2c}$$

$$d_t^+ \geq 0, d_t^- \geq 0 \qquad : \alpha_t, \beta_t \qquad \forall t \in \mathcal{T} \tag{2d}$$

$$d_t^+ \cdot d_t^- = 0 \quad (\textit{Bilinear Constraint:}) \quad \forall t \in \mathcal{T} \tag{2e}$$

The objective (2a) includes the utility $U_t(d_t)$, the payment, and the cost of investment in PV capacity. The energy balance constraint (2b) ensures that consumption equals net demand after accounting for local generation. The capacity limits (2c) bound feasible solar investment. Constraints (2d) impose non-negativity on imports and exports.

The bilinear constraint (2e) prohibits simultaneous importing and exporting. This constraint makes the problem non-convex. Fortunately, when we assume that import prices are always greater than export prices, $\pi_t^+ > \pi_t^- \forall t$, constraint (2e) is always satisfied. This is formalized in Lemma 2 (Appendix A), which we use to reformulate (2a)-(2d) without the bilinear constraint. The remaining problem is composed of a concave objective function with linear constraints and is therefore a convex optimization problem. We leverage this in the following section to derive results for the prosumer's optimal operational and investment decisions under NEM.

III. Optimal Sizing and Operational Decisions

In this section, we first describe optimal operational decisions and derive a characterization of optimal prosumer investment. We then show how operational and investment decisions respond to changes in import prices, export prices, and the marginal cost of PV.

Optimal Prosumer Operation: We apply the KKT conditions to (2a)-(2d), yielding the following optimality conditions:

$$\gamma_t = U_t'(d_t) = \pi_t^+ + \alpha_t = \pi_t^- - \beta_t, \tag{3a}$$

$$\rho - \kappa = c^g - \sum_{t \in \mathcal{T}} \mathbb{E}[\gamma_t \psi_t]. \tag{3b}$$

From complementary slackness, if $d_t^- > 0$ then $\beta_t = 0$. Analogously, if $d_t^+ > 0$ then $\alpha_t = 0$. Thus,

$$d_t^- > 0 \implies \gamma_t = U_t'(d_t) = \pi_t^- \tag{4a}$$

$$d_t^+ > 0 \implies \gamma_t = U_t'(d_t) = \pi_t^+ \tag{4b}$$

Since U_t' is strictly decreasing and invertible by assumption, (2b) and the complementary slackness conditions imply the following piecewise characterization, established in [10].

Lemma 1 (Optimal Operational Decisions)**.**

$$d_t^* = \begin{cases} \bar{d}_t^+(\pi_t^+), & g\psi_t < \bar{d}_t^+(\pi_t^+) \ (\textit{import}), \\ \bar{d}_t^-(\pi_t^-), & g\psi_t > \bar{d}_t^-(\pi_t^-) \ (\textit{export}), \\ g\psi_t, & g\psi_t \in [\bar{d}_t^+(\pi_t^+), \bar{d}_t^-(\pi_t^-)] \ (\textit{net-zero}). \end{cases} \tag{5a}$$

$$d_t^{+*} = \begin{cases} \bar{d}_t^+(\pi_t^+) - g\psi_t, & g\psi_t < \bar{d}_t^+(\pi_t^+), \\ 0, & \textit{otherwise}. \end{cases} \tag{5b}$$

[2]Note that the payment model in (1) captures many NEM variants such as *net billing*, *inflows and outflows*, and *net feed-in* [4].

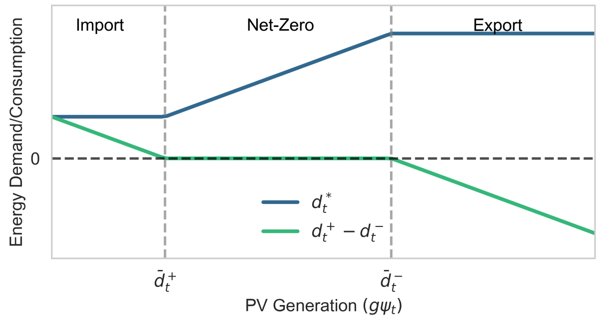

Fig. 1: Optimal consumption (blue) and optimal net demand (green) under NEM.

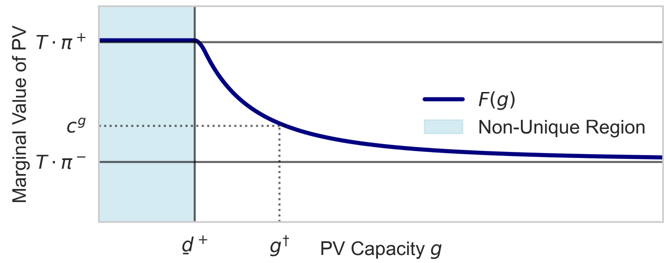

Fig. 2: The marginal value of an additional unit of PV for a prosumer.

$$d_t^{-*} = \begin{cases} g\psi_t - \bar{d}_t^-(\pi_t^-), & g\psi_t > \bar{d}_t^-(\pi_t^-), \\ 0, & \textit{otherwise}, \end{cases} \tag{5c}$$

where thresholds $\bar{d}_t^+(\pi_t^+) = \left(U_t'\right)^{-1}(\pi_t^+)$ and $\bar{d}_t^-(\pi_t^-) = \left(U_t'\right)^{-1}(\pi_t^-)$. The regimes in Equation (5a)-(5c) are illustrated by Figure 1. The blue curve shows the optimal consumption, and the green curve shows the optimal net demand given PV output $g\psi_t$. In each regime, generation $g\psi_t$ is compared to of the critical demand thresholds, $\bar{d}_t^-(\pi_t^-)$ and $\bar{d}_t^+(\pi_t^+)$. On the left side of Figure 1, generation lies below $\bar{d}_t^+(\cdot)$, and the prosumer imports electricity to compensate for the difference between generation and demand at the import price. On the right side of Figure 1, generation exceeds $\bar{d}_t^-(\cdot)$ and the prosumer consumes to the point $\bar{d}_t^-(\cdot)$, after which additional utility gains are less valuable than the compensation gained by exporting the excess PV. On the left-hand side and right-hand side of the figure, as $g\psi_t$ increases, the net demand of the prosumer decreases as generation offsets demand. Finally, if local generation lies between the two thresholds, the prosumer is at a net-zero demand from the grid, at the level of PV generation. In this regime, the slope of the net demand curve is zero as the prosumer increases their consumption to exactly match generation.

Optimal Prosumer Investment Using (3a) and (3b), we find an equilibrium condition for interior PV investment; when $g^* \in (0, \bar{g})$, $\rho = 0$ and $\kappa = 0$ due to complementary slackness. We can then characterize the marginal value of PV generation at the optimum and define the marginal value of PV:

Theorem 1 (Optimality Condition for PV Investment)**.** *The optimal PV capacity, g^*, is given by*

$$g^* = \max\{0, \min\{\bar{g}, g^\dagger\}\}, \tag{6}$$

where $g^\dagger$ is defined by the marginal value of interior PV investment determined by ψ-weighted average of the relevant period prices and marginal utilities:

$$c^g = F(g^\dagger) \tag{7a}$$

$$F(g) := \mathbb{E}\Big[\sum_{t: g\psi_t < \bar{d}_t^+} \psi_t \pi_t^+ + \sum_{t: g\psi_t \in \left[\bar{d}_t^+, \bar{d}_t^-\right]} \psi_t U_t'(\psi_t g) + \sum_{t: \psi_t g > \bar{d}_t^-} \psi_t \pi_t^- \Big]. \tag{7b}$$

Theorem 1 states that, at optimality, the marginal value of PV is equal to the marginal cost if the optimal capacity is between the maximum and minimum PV capacities. If it is at the maximum (minimum), the marginal value can exceed (resp., be less than) the marginal cost. In (7b), the marginal kW of PV capacity is valued by its capacity-factor-weighted contribution across periods: either displacing imports at price π_t^+, enabling additional consumption valued at marginal utility, or generating exports compensated at π_t^-. As $g\psi_t$ increases from zero, period t begins in the import regime, moves to the net-zero regime, and finally enters the export regime, with some periods incapable of reaching the net-zero or export regimes if $\bar{\psi}_t \bar{g}$ is smaller than $\bar{d}_t^+$ or $\bar{d}_t^-$, respectively. Because ψ_t is a continuous random variable distributed in $[0, \bar{\psi}_t]$, any period with non-zero demand that can be in the export term has a non-zero probability associated with belonging to the import or net-zero terms. Figure 2 shows a plot of the marginal value curve when there is only one period in $\mathcal{T}^g$. The flat section before $\underline{d}^+$ corresponds to when no period is in the net-zero region. After this point, the marginal value curve in Figure 2 is strictly decreasing, implying a unique solution when $g^* > \underline{d}^+$, where $\underline{d}^+ = \min_t \bar{d}_t^+$. The structure evident in Figure 2, a region of flat marginal value followed by a strictly decreasing region, describes the structure of marginal value curves beyond this illustrative example. Indeed, whenever we have a period for which there is a positive probability of the net-zero region, $F(g)$ is strictly decreasing in g. The implications of this are stated in the following corollary:

Corollary 1. *Equations* (7a)-(7b) *have a unique solution whenever $c^g \neq F(0)$. If $c^g = F(0)$, the optimal solution is set valued, $g^* \in [0, \underline{d}^+]$, and $F(g)$ is constant.*

Corollary 1 describes when optimal investment, characterized by Theorem 1, is unique or set-valued. These findings have key implications for the smoothness of investment changes in the sensitivity analysis.

Sensitivity Analysis and Comparative Statics: Using the characterization of optimal investment in Theorem 1 and Corollary 1, we perform a sensitivity analysis to better understand how changing prices cause shifts in optimal investment, optimal demand, and payments. For interior solutions, the equality in (7a) must hold even when parameters shift. Thus, the derivative of $F(g^*) - c^g$ with respect to prices and PV cost is equal to zero for interior solutions. We take the derivative, apply the chain rule, and rearrange terms to find:

$$\frac{dg^*}{d\pi_\tau^\pm} = \frac{-\frac{\partial}{\partial \pi_\tau^\pm} F(g^*)}{\frac{\partial}{\partial g} F(g^*)}, \quad \frac{dg^*}{dc^g} = \frac{1}{\frac{\partial}{\partial g} F(g^*)}. \tag{8}$$

Recall that $F(g^*)$ is decreasing in g^*. Additionally, from (7a)-(7b), we can see that the $F(\cdot)$ is increasing in $\pi_\tau^\pm$ and must increase linearly with c^g. Using these partial derivatives, we can identify how much optimal PV capacity changes with prices and PV costs:

Proposition 1. *Optimal investment is weakly increasing in $\pi_\tau^\pm$ and weakly decreasing in c^g. We further break down the movement of g^* for each of the following cases:*
Case 1 (Capacity at bounds): *If $c^g \notin [F(\bar g), F(0)]$, then $g^* \in \{0, \bar g\}$ and $dg^*/d\pi_\tau^+ = dg^*/d\pi_\tau^- = dg^*/dc^g = 0$.*
Case 2 (Interior capacity): *If $c^g \in (F(\bar g), F(0))$ and $g^* \notin \{\bar d_t^+\}_{t\in\mathcal{T}^g}$. Then*

$$\frac{dg^*}{d\pi_\tau^+} = \frac{-\mathbb{E}[\psi_\tau \cdot \mathbb{1}\{\psi_\tau g^* < \bar d_\tau^+\}]}{\mathbb{E}[\sum_{t:\,\psi_t g^* \in (\bar d_t^+, \bar d_t^-)} \psi_t^2\, U_t''(\psi_t g^*)]} > 0, \tag{9a}$$

$$\frac{dg^*}{d\pi_\tau^-} = \frac{-\mathbb{E}[\psi_\tau \cdot \mathbb{1}\{\psi_\tau g^* > \bar d_\tau^-\}]}{\mathbb{E}[\sum_{t:\,\psi_t g^* \in (\bar d_t^+, \bar d_t^-)} \psi_t^2\, U_t''(\psi_t g^*)]} > 0, \tag{9b}$$

$$\frac{dg^*}{dc^g} = \frac{1}{\mathbb{E}[\sum_{t:\,\psi_t g^* \in (\bar d_t^+, \bar d_t^-)} \psi_t^2\, U_t''(\psi_t g^*)]} < 0. \tag{9c}$$

When $g^* \in \{\bar d_t^+\}_{t\in\mathcal{T}^g}$, replace (9a)-(9c) *with the corresponding left/right directional derivatives.*
Case 3 (Entry/Exit points): *If $F(0) = c^g$, the left-and right-hand derivatives are* 0 *and* (9a)-(9b) *for $\pi_\tau^\pm$, and* (9c) *and* 0 *for c^g. The directional derivatives are reversed when $F(\bar g) = c^g$.*

Proposition 1 establishes that optimal PV capacity is weakly decreasing in PV costs and weakly increasing in both import and export prices. For interior solutions, the response of g^* is smooth and governed by the marginal value condition in Theorem 1: changes in prices or costs must be offset by adjustments in capacity so as to preserve the equality between the expected marginal value of PV and its marginal cost.

The expressions in Case 2 make explicit how this adjustment depends on which operational regimes are active. Capacity changes are larger when periods have greater probability of being in the import or export regimes and smaller when periods have greater probability of being in the net-zero regime. Since marginal value in the net-zero region is given by $U'(\cdot)$ and is decreasing, additional capacity delivers declining value, which dampens the overall response of net demand to price changes. This causes the reduced sensitivity of net demand when generation is likely to fall in the net-zero regime.

The remaining cases complete the characterization of the capacity response to changes in parameters. When $c^g \notin [F(\bar g), F(0)]$, optimal capacity is at the bounds and small price changes have no effect on PV capacity. Around the entry point $F(0) = c^g$, the optimal capacity changes discretely, but the jump is limited to $\underline{d}^+$ and preserves monotonicity in all variables. Thus, Proposition 1 implies that parameter changes induce at most one discrete adjustment in PV capacity, followed by a region of continuous response.

Changes in PV capacity have important implications for how operational decisions are altered by price changes. We demonstrate the effect of PV changes by decomposing the impact of an import price change on the optimal demand into direct and PV effects:

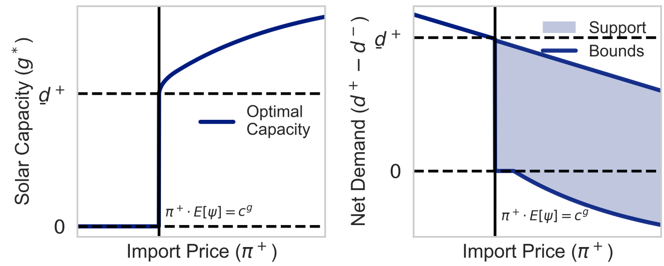

Fig. 3: **Left:** Optimal PV as a function of the import price π^+. **Right:** Distribution of net demand for a single period as a function of the import price.

$$\frac{d}{d\pi_\tau^+}\,\mathbb{E}\big[d_t^{+*} - d_t^{-*}\big] \tag{10}$$

$$= \underbrace{\mathbb{1}\{t=\tau\}\cdot\frac{\mathbb{P}\big(\psi_\tau g^* < \bar d_\tau^+\big)}{U_\tau''(\bar d_\tau^+)}}_{\text{direct effect}} \underbrace{-\mathbb{E}\Big[\sum_{t:\,\psi_t g^* < \bar d_t^+}\psi_t \;+ \sum_{t:\,\psi_t g^* > \bar d_t^-}\psi_t\Big]\cdot\frac{\partial g^*}{\partial \pi_\tau^+}}_{\text{PV effect}}.$$

The decomposition in (10) highlights two distinct channels through which price changes affect net demand. The direct effect captures the within-period response: a change in π_τ^+ alters $\bar d_t^+$ only for period $t=\tau$ and only when the prosumer is importing. The PV effect captures the effect of a change in optimal PV capacity adjustment: when prices change prosumers adjust PV investment, which in turn shifts net demand across all periods with positive generation.

Figure 3 visualizes these effects using a one period example. The left panel shows how optimal PV investment responds to changes in π^+, including the discrete jump in capacity when $c^g = F(0)$, the monotonic increase of PV capacity after this jump, and eventual saturation of PV capacity at $\bar g$ (not depicted). The right panel shows how these investment responses translate into net-demand outcomes. When PV capacity is zero, each π^+ corresponds to a single net-demand value. Once $g^* > 0$, net demand spans a range due to variation in ψ. The downward slope of the upper bound reflects the direct effect of demand response to higher import prices, while the downward slope of the lower bound reflects the PV effect: as capacity increases, net demand continues to fall even in the export state when the prosumer is not directly exposed to π^-.

Taken together, the analysis exposes four phenomena. First, price changes induce a direct, within-period response in net demand when the prosumer is exposed to the relevant price. Second, through the PV effect, price changes also alter net demand in other periods and regimes by shifting optimal PV capacity. Third, optimal PV investment exhibits a non-smooth entry threshold, followed by a continuous adjustment region and eventual saturation, which governs when the PV effect becomes active and how strongly it operates. Fourth, net-zero self-consumption periods dampen the investment response to price and cost changes, as additional generation is valued at declining marginal utility rather than market prices.

Endogenizing PV capacity also has important implications for payments, a central object for tariff design. For increases in the import or export price, treating PV capacity as fixed overestimates the resulting change in payment, as it ignores the

TABLE II: Comparative statics analysis

Variable	$c^g \uparrow$			$\pi_\tau^+ \uparrow$			$\pi_\tau^- \uparrow$		
Region	$+$	0	$-$	$+$	0	$-$	$+$	0	$-$
d_τ^*	-	$\downarrow$	$\downarrow$	$\downarrow$	$\uparrow$	-	-	$\uparrow$	$\downarrow$
$d_\tau^{+*} - d_\tau^{-*}$	$\uparrow$	-	$\uparrow$	$\downarrow$	-	$\downarrow$	$\downarrow$	-	$\downarrow$
d_t^*				-	$\uparrow$	-	-	$\uparrow$	-
$d_t^{+*} - d_t^{-*}$				$\downarrow$	-	$\downarrow$	$\downarrow$	-	$\downarrow$
$P^{\text{NEM}*}$	$\uparrow$	-	$\uparrow$	X	-	$\downarrow$	$\downarrow$	-	$\downarrow$
S^*	$\downarrow$	$\downarrow$	$\downarrow$	X	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$

$\uparrow$ increase; $\downarrow$ decrease; - Unchanged; X Indeterminate.

capacity adjustment that lower net demand across generating periods. With endogenous PV, increases in capacity lower net demand. This causes payment to rise less, or fall more, in response to import/export price increases than in the fixed-capacity case. Proposition 2 (Appendix F) formalizes this decomposition into direct and PV effects.

Finally, Table II summarizes the comparative statistics for investment, net demand, payment, and surplus. Changes in c^g affect outcomes only through PV investment, whereas changes in $\pi_\tau^\pm$ combine direct and PV effects. Because P^{NEM} and S^* aggregate outcomes across periods, the reported comparative statistics should be interpreted as changes in total payment or surplus contributions summed over relevant regime's periods.

IV. Case Study - A Household in Massachusetts

We conduct a case study for a single family home in Massachusetts under a NEM tariff.[3] To generate the parameters necessary for this case study, we use simulated hourly demand profiles and PV generation data for 2018 from the NREL ResStock dataset [17]. We parameterize the utility function of every period t (and the implied inverse-demand curves used in the surplus and payment calculations), using the same estimation approach as in the appendix of Alahmed and Tong [4]. To represent uncertainty in PV output within each settlement period, we modeled the capacity factor using a normal random variable clipped to $[0, 1]$: for each period t, we take the mean capacity factor from the profile in the ResStock simulated data and choose the standard deviation to match the month-specific standard deviation for capacity factors reported by Campbell et al. [18]. Their estimates do not exactly match the time scale of our monthly peak/off-peak periods, but provide a rough scale for the standard deviation of the capacity factors and was more appropriate than using a standard deviation derived for yearly, daily, or hourly data. Additional details are provided in Appendix H.

We evaluated household operation and investment under four NEM tariffs. Each has different price settings based on summer/non-summer and peak/off-peak designations. Table III summarizes the import and export price parameters used in the case study. For those with summer/non-summer differences, summer is defined as June-August. The *Symmetric* prices are based upon current Massachusetts rates, and the compensation

[3]Under Gorman aggregation [16], the quadratic utility specification admits a representative consumer representation, and the derived responses carry over to a heterogeneous population by summation.

TABLE III: Description of tariff designs.

	Summer				Non-Summer			
Tariff	π_{pk}^+	π_{op}^+	π_{pk}^-	π_{op}^-	π_{pk}^+	π_{op}^+	π_{pk}^-	π_{op}^-
Symmetric	0.35	-	0.35	-	0.35	-	0.35	-
Asymmetric	0.35	0.35	0.16	0.16	0.35	0.35	0.16	0.16
Proposed	0.73	0.29	0.73	0.29	0.48	0.29	0.48	0.29
Prop.-Asym.	0.73	0.29	0.25	0.20	0.48	0.29	0.15	0.10

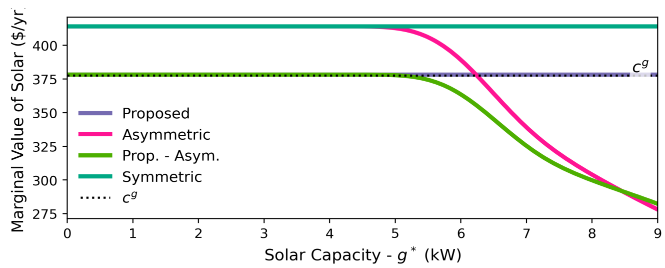

Fig. 4: Marginal value of an additional unit of PV capacity.

for exports is equal to that of imports. There is no peak/offpeak designation, and although this tariff has a peak period, it is the only period and captures all hours of the day. *Proposed* prices are based upon a current proposal for time-of-use rates in Massachusetts.[4] The billing periods are distinguished by peak/off-peak periods, with peak hours between 4pm and 8pm. Similarly to *Symmetric*, import prices under *Proposed* are equal to export prices. Finally, *Asymmetric* and *Prop.-Asym.* tariffs are not based upon current prices or suggested prices in Massachusetts. We constructed them to illustrate how prosumer PV investment and operations for asymmetrical prices that are similar to current and proposed tariffs.

Figure 4 illustrates the marginal value of an incremental increase in installed PV capacity, (7b), to the prosumer in our case study for each tariff in Table III. When prices are symmetric, marginal values are constant, and PV investments will be all-or-nothing. There is almost no net-zero region as $\bar{d}_t^+ = \bar{d}_t^- + \epsilon$ with $\epsilon = 10^{-6}$. In contrast, when prices are asymmetric, the net-zero regime gives the marginal value function, $F(\cdot)$, curvature. At some point for both asymmetric tariffs, PV generation is sufficient to push some periods into the net-zero or export regimes. This decreases the profitability of larger installations under asymmetric tariffs relative to symmetric tariffs and smooths PV capacity changes so that optimal investment is no longer all-or-nothing. Instead, the jump is limited and elsewhere optimal capacity moves continuously with parameter changes (as discussed in Proposition 1).

For *Symmetric*, *Asymmetric*, and *Proposed*, Figure 5 provides contour plots of optimal installed PV capacity, total net demand with endogenized PV capacity, total net demand when PV capacity is fixed, total prosumer payment with endogenized PV capacity, and total prosumer payment when PV capacity is fixed. For fixed PV capacity, we use the optimal PV capacity at the original tariffs, *i.e.,* the tariffs without any changes to import or export prices. We set $c^g = 377.67$ \$/kW and $\bar{g} = 9$ kW (Appendix H). Import prices vary from baseline in all periods by 0–0.15 \$/kWh, and export prices vary from baseline

[4]See Massachussets Department of Energy Resources time-of-use proposal.

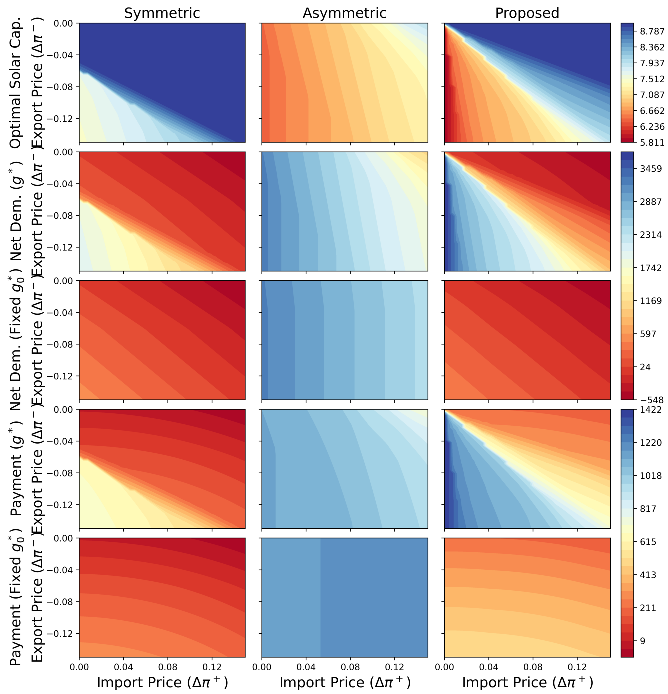

Fig. 5: Contour plots comparing the impact of price changes on the prosumer's optimal PV capacity, total net demand with optimal PV capacity, total net demand with fixed PV capacity, total payment with optimal PV capacity, and total payment with fixed PV capacity.

in all periods by -0.15–0 \$/kWh (baselines are detailed in Table III). Figure 5 highlights several results from Section III: **(i)** Optimal PV capacity is monotonically increasing in the import and export prices, as indicated by Prop. 1. **(ii)** Net demand decreases in import and export prices due to an increase in generation and a decrease in consumption, reflecting the negative sign of the derivative in (10). **(iii)** The combination of increasing payment per unit, decreasing demand, and increasing PV generation leads to a non-monotonic effect of import prices on payment, described in Prop. 2 and visible in the contrast between *Asym.* and *Prop.* in the fourth row (payment under optimal adoption). Payment under *Prop.* sharply decreases in the import price as PV is added. Under *Asym.*, payment increases in the import price, reflecting a more gradual addition of PV and changes to net demand. In contrast to the import price, we can observe a monotonic increase of payment in the export price in the fourth and fifth rows. While not shown here, prosumer surplus decreases (increases) monotonically with import (resp. export) price. Thus, there may be certain regions for which an increase in import price lowers both the payment of the prosumer and their payment to the DU, representing a loss for both parties. **(iv)** Comparing the endogenous-PV rows to their fixed-PV counterparts (rows 2 vs. 3 and rows 4 vs. 5) shows that allowing PV capacity to adjust materially changes the implied sensitivity of both net demand and payment to changes in tariffs. This also reflects the difference in our analysis compared with those that fix PV capacity and analyze operations [10], [11]. In particular, an increase in the import price produces a smaller increase in payment under endogenous PV than under fixed PV (and in some regions a larger decrease), whereas a decrease in the export price produces a larger increase in payment under endogenous PV than under fixed PV. Figure 5 demonstrates that the importance of endogenous PV capacity to changes in net demand and payment discussed in Section III are not just theoretical artifacts but apply to our case study

V. Conclusion

This paper characterizes the joint investment and operational decisions of flexible prosumers with BTM PV generation under asymmetric, time-varying NEM tariffs. Endogenizing PV capacity, we derive conditions that link optimal investment to the marginal value of PV generation across three operational regimes: import, net-zero consumption, and export.

Asymmetric import and export prices give rise to a net-zero self-consumption region, which plays a central role in shaping investment incentives. Optimal PV capacity increases with import and export prices, but its sensitivity to price changes is attenuated when a larger share of generation falls in the net-zero regime, where additional generation is valued at declining marginal utility rather than fixed market prices.

Endogenizing PV capacity reveals a cross-period and regime PV effect: tariff changes in one period affect net demand and consumption in all periods with positive generation through adjustments in optimal PV capacity. This effect has direct implications for DU cost recovery. An increase in the import price raises payments per unit imported, but may also induce additional PV investment that reduces net imports. The resulting additional investment attenuates or even reverses the payment increase. By contrast, a decrease in the export price increases DU payments both directly, by reducing compensation for exported generation, and indirectly, by reducing the private return to additional PV capacity. Ignoring investment responses therefore overstates the revenue impact of import price increases and understates the impact of export price decreases. If regulators seek to increase DU payments from current PV owners, export price reductions are generally a more targeted instrument than import-price increases. Import price increases also affect customers without PV. Some of these customers may be prospective adopters and an increase in the import price encourages additional PV adoption. Others will remain non-adopters, and would pay more under a higher import price. If regulators want to leave payments from this latter group unchanged, export-price reductions do not increase payments from customers without PV. This distinction becomes increasingly important as rooftop PV costs fall and regulators reconsider NEM compensation.

A case study based on Massachusetts demand, PV generation, and tariffs illustrates our analytic findings under realistic conditions, highlighting the importance of accounting for endogenous PV investment when evaluating NEM tariffs.

This work opens several avenues for future research. Successor NEM tariffs motivate joint investment and operational analysis of PV-battery systems. Another direction is to study the co-evolution of tariff design and distributed PV investment under the feedback between policy and consumer adoption.

VI. AI Usage Disclosure

During the preparation of this manuscript, the authors used ChatGPT for content assistance, specifically in drafting and condensing exposition. The authors reviewed and revised the material generated and assume full responsibility for the content of this publication.

Appendix

A. Statement and Proof of Lemma 2

Lemma 2. *Suppose $\pi_t^+ > \pi_t^-$ for all t. Then, for any solution to (2) that is optimal, we have $d_t^+ \cdot d_t^- = 0 \quad \forall\, t$.*

Fix t and consider any feasible point. If at most one of d_t^+, d_t^- is positive, the condition already holds. So assume $d_t^+ > 0$ and $d_t^- > 0$.

Pick any $\varepsilon \in (0, \min\{d_t^+, d_t^-\})$ and define $\tilde{d}_t^+ := d_t^+ - \varepsilon, \tilde{d}_t^- := d_t^- - \varepsilon$. Then $\tilde{d}_t^+ \geq 0$, $\tilde{d}_t^- \geq 0$, and

$$\tilde{d}_t^+ - \tilde{d}_t^- = (d_t^+ - \varepsilon) - (d_t^- - \varepsilon) = d_t^+ - d_t^- = d_t - \psi_t g,$$

so the power-balance constraint (2b) remains satisfied. Since we are only changing d_t^+, d_t^- and keeping d_t fixed, the consumption utility term $U_t(d_t)$ is unchanged, as are $-c^g g$ and π^c. The only part of the objective in (2a) that changes in period t is $-\pi_t^+ d_t^+ + \pi_t^- d_t^-$. Under the modified pair,

$$-\pi_t^+ \tilde{d}_t^+ + \pi_t^- \tilde{d}_t^- = \big(-\pi_t^+ d_t^+ + \pi_t^- d_t^- \big) + \varepsilon(\pi_t^+ - \pi_t^-).$$

Because $\pi_t^+ \geq \pi_t^-$, we have $\varepsilon(\pi_t^+ - \pi_t^-) \geq 0$, with strict inequality if $\pi_t^+ > \pi_t^-$. Thus the modified point is feasible and yields an objective value that is weakly larger (strictly larger when $\pi_t^+ > \pi_t^-$) than the original one. Repeating this reduction step until one of d_t^+, d_t^- hits zero produces a feasible point with weakly higher objective value and $d_t^+ d_t^- = 0$. Hence no optimal solution can have $d_t^+ > 0$ and $d_t^- > 0$. ■

Lagrangian The Lagrangian associated with problem (2) is

$$\begin{aligned}\mathcal{L} =& \mathbb{E}\Big[\sum_{t\in\mathcal{T}} (U_t(d_t) - \pi_t^+ d_t^+ + \pi_t^- d_t^-)\Big] - c^g g - \pi^c \\ &+ \mathbb{E}\Big[\sum_{t\in\mathcal{T}} (-\alpha_t d_t^+ - \beta_t d_t^- + \gamma_t(d_t^+ - d_t^- - d_t + \psi_t g))\Big] \\ &- \kappa g + \rho(g - \bar{g}) \end{aligned} \tag{11}$$

where $\alpha_t, \beta_t, \kappa, \rho \geq 0$ and $\gamma_t \in \mathbb{R}$. The expectation is taken with respect to the distribution of capacity factors ψ_t.

Stationarity: The stationarity conditions are

$$\frac{\partial \mathcal{L}}{\partial d_t} = U_t'(d_t) - \gamma_t = 0, \tag{12a}$$

$$\frac{\partial \mathcal{L}}{\partial d_t^+} = -\pi_t^+ - \alpha_t + \gamma_t = 0, \frac{\partial \mathcal{L}}{\partial d_t^-} = \pi_t^- - \beta_t - \gamma_t = 0, \tag{12b}$$

$$\frac{\partial \mathcal{L}}{\partial g} = -c^g - \kappa + \rho + \mathbb{E}\Big[\sum_{t\in\mathcal{T}} \gamma_t \psi_t\Big] = 0. \tag{12c}$$

Primal Feasibility: Primal feasibility entails,

$$d_t^+ \geq 0,\ d_t^- \geq 0,\ 0 \leq g \leq \bar{g},\ d_t^+ - d_t^- - d_t + \psi_t g = 0,$$

holding almost surely.

Dual Feasibility: These are are $\alpha_t,\ \beta_t,\ \kappa,\ \rho \geq 0$,.

Complementary Slackness:

$$\alpha_t d_t^+ = 0, \quad \beta_t d_t^- = 0, \quad \kappa g = 0, \quad \rho(g - \bar{g}) = 0.$$

B. Proof of Lemma 1:

From (12a) and (12b),

$$\begin{aligned} \gamma_t = U_t'(d_t) = \pi_t^+ + \alpha_t = \pi_t^- - \beta_t, \\ \rho - \kappa = c^g - \mathbb{E}\Big[\sum_{t\in\mathcal{T}} \gamma_t \psi_t\Big]. \end{aligned}$$

From complementary slackness, if $d_t^- > 0$ then $\beta_t = 0$. Analogously, if $d_t^+ > 0$ then $\alpha_t = 0$. Thus,

$$d_t^- > 0 \Longrightarrow \gamma_t = U_t'(d_t) = \pi_t^-,\ d_t^+ > 0 \Longrightarrow \gamma_t = U_t'(d_t) = \pi_t^+.$$

Next use the balance constraint $d_t^+ - d_t^- = d_t - g\psi_t$. If $d_t > g\psi_t$, then $d_t - g\psi_t > 0$ so we must have $d_t^+ > 0$ (and therefore $d_t^- = 0$); thus, $d_t = \bar{d}_t^+(\pi_t^+)$, and substituting into the balance constraint gives $d_t^+ = \bar{d}_t^+(\pi_t^+) - g\psi_t$, $d_t^- = 0$. Feasibility requires $\bar{d}_t^+(\pi_t^+) > g\psi_t$, which is exactly the import condition.

If $d_t < g\psi_t$, then $d_t - g\psi_t < 0$ so we must have $d_t^- > 0$ (and therefore $d_t^+ = 0$); thus $d_t = \bar{d}_t^-(\pi_t^-)$ and $d_t^- = g\psi_t - \bar{d}_t^-(\pi_t^-)$, $d_t^+ = 0$. Feasibility then requires $g\psi_t > \bar{d}_t^-(\pi_t^-)$.

Finally, if neither feasibility condition holds, *i.e.,* $g\psi_t \in [\bar{d}_t^+(\pi_t^+),\ \bar{d}_t^-(\pi_t^-)]$, then the two strict cases above are infeasible. The only feasible point satisfying the balance constraint with $d_t^+ = d_t^- = 0$ is $d_t = g\psi_t$, which yields the net-zero regime. Substituting into the balance constraint gives $d_t^+ = d_t^- = 0$. Combining the three cases yields (5a)-(5c). ■

C. Proof of Theorem 1:

Any optimal solution satisfies the stationarity condition (3b). In particular, if $0 < g < \bar{g}$ then $\kappa = \rho = 0$ and hence,

$$c^g = \mathbb{E}\Big[\sum_{t\in\mathcal{T}} \gamma_t \psi_t\Big], \tag{14}$$

which is equivalent to (7a) Using $\gamma_t = U_t'(d_t)$ from (3a) and complementary slackness from (4a)-(4b), γ_t equals π_t^+ in the import regime, π_t^- in the export regime, and $U_t'(\psi_t g)$ in the net-zero regime. Using Lemma 1 to express these regimes as conditions on $\psi_t g$ relative to $\bar{d}_t^+$ and $\bar{d}_t^-$, the right-hand side of (14) can be re-expressed as $F(g)$ in (7b). Thus any interior optimum $g^\dagger$ satisfies $c^g = F(g^\dagger)$.

Finally, since the feasible set for g is the interval $[0, \bar{g}]$, if an interior solution exists it must be $g^\dagger$, and otherwise the optimum is at a boundary. Equivalently, the optimal capacity is the projection of $g^\dagger$ onto $[0, \bar{g}]$,

$$g^* = \max\{0, \min\{\bar{g},\ g^\dagger\}\},$$

which is (6). ■

D. Proof of Corollary 1

For any $g \in [0, \underline{d}^+]$ and any realization of $\psi_t \in [0, \bar{\psi}_t]$, then $\psi_t g \leq \bar{d}_t^+$ for all t, implying that all periods remain in the import regime almost surely. Hence, $F(g) = F(0), \quad g \in [0, \underline{d}^+]$, so $F(\cdot)$ is constant on $[0, \underline{d}^+]$ and therefore not invertible on this interval. For any $g > \underline{d}^+$, there exists at least one period t such that

$$\mathbb{P}\big(\bar{d}_t^- < \psi_t g < \bar{d}_t^+\big) > 0.$$

Since boundary events have probability zero, differentiation under the expectation yields

$$\frac{\partial F}{\partial g}(g^*; \pi) = \mathbb{E}\Big[\sum_{t\in\mathcal{T}} \psi_t^2\, U_t''(\psi_t g)\, \mathbb{1}\{\bar{d}_t^- < \psi_t g < \bar{d}_t^+\}\Big]. \tag{15}$$

The contribution for every period is non-positive, and at least one is strictly negative with positive probability. Thus,

$$\frac{\partial F}{\partial g}(g^*;\pi) < 0 \qquad \forall g \in (\underline{d}^+, \bar{g}), \tag{16}$$

so $F(\cdot)$ is strictly decreasing and therefore invertible on $(\underline{d}^+, \bar{g})$. Consequently, the equation $F(g) = c^g$ has a unique interior solution $g^\dagger$ whenever $c^g \in \big(F(\bar{g}),\, F(\underline{d}^+)\big)$ and, by extension, whenever $c^g < F(0)$. The flat region $[0, \underline{d}^+]$ is the only source of non-uniqueness; beyond this region, continuous ψ eliminates all discrete jumps in $F(\cdot)$.

E. Proof of Proposition 1

Recall that $F(\cdot)$ is weakly decreasing in g (strictly decreasing whenever the net-zero region has positive probability), while it is weakly increasing in each $\pi_\tau^\pm$.

Case 1 (Capacity at bounds). If $c^g \notin [F(\bar{g}), F(0)]$, then (7a) has no interior solution. So $g^* \in \{0, \bar{g}\}$. For local perturbations of (π_τ^+, π_τ^-) and c^g that keep $c^g \notin [F(\bar{g}), F(0)]$, the argmax remains at the same boundary point, hence $dg^*/d\pi_\tau^+ = dg^*/d\pi_\tau^- = dg^*/dc^g = 0$.

Case 3 (Entry/Exit points). If $F(0) = c^g$, the boundary solution $g^* = 0$ is optimal. For one-sided perturbations that move into the interior region (i.e., make $c^g \in (F(\bar{g}), F(0))$), the optimal g^* becomes interior and its right-derivatives are given by the interior formulas in Case 2 (evaluated at the right limit), while the left-derivatives remain 0 since g^* stays pinned at 0. Thus the left- and right-hand derivatives are 0 and (9a)-(9b) for $\pi_\tau^\pm$, and (9c) and 0 for c^g. The same argument applies at $F(\bar{g}) = c^g$, with left/right reversed since the boundary solution is then $g^* = \bar{g}$.

Case 2 (Interior capacity). Now suppose $c^g \in (F(\bar{g}), F(0))$ and $g^* \notin \{\bar{d}_t^+\}_{t\in\mathcal{T}^g}$. Then $g^* \in (0, \bar{g})$ and F is differentiable at g^*, so differentiating $F(g^*) - c^g$ with respect to any parameter $\theta \in \{\pi_\tau^+, \pi_\tau^-, c^g\}$ yields

$$0 = \frac{\partial F}{\partial g}(g^*;\pi)\frac{dg^*}{d\theta} + \frac{\partial}{\partial\theta}\big(F(g^*;\pi) - c^g\big), \tag{17}$$

and hence,

$$\frac{dg^*}{d\theta} = -\frac{\partial(F - c^g)/\partial\theta}{\partial F/\partial g}.$$

Because ψ_t is continuously distributed, regime boundary events have probability zero, so we may differentiate under the expectation. On any neighborhood with no regime switches,

$$\frac{\partial F}{\partial g}(g^*;\pi) = \mathbb{E}\Big[\sum_{t:\,\psi_t g^* \in (\bar{d}_t^+, \bar{d}_t^-)} \psi_t^2\, U_t''(\psi_t g^*)\Big] \;<\; 0, \tag{18}$$

since $U_t'' < 0$.

For π_τ^+, only the import regime in period τ depends on π_τ^+,

$$\frac{\partial F}{\partial \pi_\tau^+}(g^*;\pi) = \mathbb{E}\big[\psi_\tau\, \mathbb{1}\{\psi_\tau g^* < \bar{d}_\tau^+\}\big] \;\geq\; 0, \tag{19}$$

and for π_τ^-, only the export regime depends on π_τ^-,

$$\frac{\partial F}{\partial \pi_\tau^-}(g^*;\pi) = \mathbb{E}\big[\psi_\tau\, \mathbb{1}\{\psi_\tau g^* > \bar{d}_\tau^-\}\big] \;\geq\; 0. \tag{20}$$

Finally, $\partial(F - c^g)/\partial c^g = -1$. Substituting (18)-(20) into (17) yields (9a)-(9c). Since (18) is negative and (19)-(20) are positive, it follows that g^* is weakly increasing in $\pi_\tau^\pm$ and weakly decreasing in c^g.

If $g^* \in \{\bar{d}_t^+\}_{t\in\mathcal{T}^g}$, F need not be differentiable; applying the same argument to left and right limits yields the corresponding directional derivatives. ■

F. Proposition 2 and its Proof

Proposition 2. *At points where g^* is differentiable, the expected NEM payment varies with changes in the import or export price in period τ as*

$$\frac{\partial}{\partial \pi_\tau^\pm}\mathbb{E}[P^{\text{NEM}*}] = \underbrace{\mathbb{E}\Big[\pm\, d_\tau^{\pm*}\Big] + \pi_\tau^\pm \frac{1}{U_\tau''\big(\bar{d}_\tau^\pm(\pi_\tau^\pm)\big)}\,\mathbb{P}\big(d_\tau^{\pm*} > 0\big)}_{\textit{direct effect}}$$
$$\underbrace{-\mathbb{E}\Big[\sum_{t:\psi_t g^* < \bar{d}_t^+(\pi_t^+)} \pi_t^+ \psi_t + \sum_{t:\psi_t g^* > \bar{d}_t^-(\pi_t^-)} \pi_t^- \psi_t\Big] \cdot \frac{\partial g^*}{\partial \pi_\tau^\pm}}_{\textit{PV effect}}. \tag{21}$$

Proof: Write the (expected) optimal payment as $\mathbb{E}[P^{\text{NEM}*}(\pi)] = \bar{P}(g^*(\pi), \pi)$, where $\bar{P}(g, \pi)$ is defined by (1) with $(d_t^{+*}(g,\pi), d_t^{-*}(g,\pi))$ given by Lemma 1. At any point where $g^*(\cdot)$ is differentiable, the chain rule gives

$$\mathbb{E}\Big[\frac{\partial}{\partial \pi_\tau^\pm} P^{\text{NEM}*}\Big] = \frac{\partial}{\partial \pi_\tau^\pm}\bar{P}(g^*, \pi) + \frac{\partial}{\partial g}\bar{P}(g^*, \pi) \cdot \frac{\partial g^*}{\partial \pi_\tau^\pm}. \tag{22}$$

For the direct term, only the τ-terms vary with $\pi_\tau^\pm$ at fixed g^*. Using Lemma 1, $d_\tau^{+*}(g^*, \pi) = [\bar{d}_\tau^+(\pi_\tau^+) - \psi_\tau g^*]^+$ and $d_\tau^{-*}(g^*, \pi) = [\psi_\tau g^* - \bar{d}_\tau^-(\pi_\tau^-)]^+$. Differentiating $\mathbb{E}[\pi_\tau^\pm d_\tau^{\pm*}]$ w.r.t. $\pi_\tau^\pm$ and using $\frac{d}{d\pi_\tau^\pm}\bar{d}_\tau^\pm(\pi_\tau^\pm) = 1/U_\tau''(\bar{d}_\tau^\pm(\pi_\tau^\pm))$ yields the direct-effect term in (21).

For the PV term, differentiate $\bar{P}(g, \pi)$ w.r.t. g using Lemma 1: $\partial d_t^{+*}/\partial g = -\psi_t\, \mathbb{1}\{\psi_t g < \bar{d}_t^+(\pi_t^+)\}$ and $\partial d_t^{-*}/\partial g = \psi_t\, \mathbb{1}\{\psi_t g > \bar{d}_t^-(\pi_t^-)\}$ a.s., so

$$\frac{\partial}{\partial g}\bar{P}(g^*, \pi) = -\mathbb{E}\Big[\sum_{t:\psi_t g^* < \bar{d}_t^+(\pi_t^+)} \pi_t^+ \psi_t + \sum_{t:\psi_t g^* > \bar{d}_t^-(\pi_t^-)} \pi_t^- \psi_t\Big]. \tag{23}$$

Substituting (23) into (22) gives (21). ■

G. Justification of Table II.

All comparative statics are local and evaluated at points where regimes do not switch; boundary events have probability zero under the assumed continuity of ψ_t. We use on Lemma 1 for the piecewise form of $(d_t^*, d_t^{+*} - d_t^{-*})$ and on Proposition 1 for the signs of $dg^*/d\pi_\tau^\pm$ and dg^*/dc^g.

a) Own-period quantities (first row): For period τ, $d_\tau^* = \bar{d}_\tau^+(\pi_\tau^+)$ in the import region, $d_\tau^* = g^*\psi_\tau$ in the net-zero region, and $d_\tau^* = \bar{d}_\tau^-(\pi_\tau^-)$ in the export region. Hence, under $c^g \uparrow$, only the net-zero case responds locally and decreases since $dg^*/dc^g < 0$. Under $\pi_\tau^+ \uparrow$, d_τ^* decreases in import (by $\frac{d}{d\pi}\bar{d}_\tau^+ < 0$), increases in net-zero (since $dg^*/d\pi_\tau^+ > 0$), and is unchanged in export. Under $\pi_\tau^- \uparrow$, d_τ^* is unchanged in import, increases in net-zero, and decreases in export (by $\frac{d}{d\pi}\bar{d}_\tau^- < 0$).

For net demand, $d_\tau^{+*} - d_\tau^{-*} = \bar{d}_\tau^+(\pi_\tau^+) - g^*\psi_\tau$ in import, 0 in net-zero, and $\bar{d}_\tau^-(\pi_\tau^-) - g^*\psi_\tau$ in export. Thus $c^g \uparrow$ raises net demand in both import and export, while leaving the net-zero case unchanged. An increase in either π_τ^+ or π_τ^- lowers net demand in both import and export (directly through $\bar{d}_\tau^\pm$ when applicable and indirectly through g^*).

b) Other period quantities ($t \neq \tau$): When only (π_τ^+, π_τ^-) changes, $\bar{d}_t^\pm(\pi_t^\pm)$ is unaffected for $t \neq \tau$; the only channel is g^*. Hence $d_t^* = g^*\psi_t$ increases in the net-zero region and is locally unchanged in import and export, while $d_t^{+*} - d_t^{-*}$ decreases in both import and export and remains zero in net-zero. This yields the middle block of the table.

c) Payments: Payment responses follow from Proposition 2 by combining a regime-specific direct effect in period τ with a PV effect operating through $dg^*/d(\cdot)$. If period τ is net-zero, neither channel is active locally and payment is unchanged. If period τ is importing, an increase in π_τ^+ raises the per-unit import charge but also induces additional PV investment that reduces net imports across generating periods, rendering the net payment effect indeterminate. If period τ is exporting, π_τ^+ affects payment only through the PV channel, yielding a decrease. By contrast, increases in π_τ^- reduce expected payment whenever period τ exports, since both the direct and PV effects act in the same direction. Finally, when c^g increases, only the PV channel operates via $dg^*/dc^g < 0$, and the resulting payment changes follow directly from the sign of $\partial P^{\mathrm{NEM}}/\partial g$, as summarized in Table II.

d) Surplus: Surplus results follow from the envelope theorem. For total surplus,

$$\frac{\partial S^*}{\partial c^g} = -g^* \leq 0, \;\; \frac{\partial S^*}{\partial \pi_\tau^+} = -\mathbb{E}[d_\tau^{+*}] \leq 0, \;\; \frac{\partial S^*}{\partial \pi_\tau^-} = \mathbb{E}[d_\tau^{-*}] \geq 0.$$

Thus, total surplus weakly decreases when $c^g \uparrow$, weakly decreases when $\pi_\tau^+ \uparrow$, and weakly increases when $\pi_\tau^- \uparrow$.

These aggregate effects can differ from the signs of period surplus components. When $c^g \uparrow$, g^* weakly decreases, so period surplus weakly decreases in all regimes: consumption falls in net-zero periods, imports rise in import periods, and exports fall in export periods. When $\pi_\tau^+ \uparrow$, g^* weakly increases. For $t \neq \tau$, prices are unchanged, so period surplus weakly increases in all regimes: imports fall in import periods, consumption rises in net-zero periods, and exports rise in export periods. For $t = \tau$, the import-regime surplus component combines the direct loss from the higher import price with the positive investment channel, so its sign is generally indeterminate; in the net-zero and export regimes, there is no direct import-price effect and period-level operating surplus weakly increases through the investment channel. When $\pi_\tau^- \uparrow$, g^* weakly increases. The own-period-export surplus component also increases directly, so period surplus weakly increases in all regimes.

H. Case Study

PV Parameters: We use $\bar{g} = 9$ kW as this corresponds to the value in the ResStock dataset for the single-family home we use in the case study (id $= 46985$). We use the following calculation to derive the yearly amortized cost of a kW of PV:

$$c^g = 12 \cdot C \frac{r}{1 - (1+r)^{-n}},$$

where $C = 2900$ \$/kW, $r = 0.055/12$, and $n = 120$, corresponding to a 10 year, 5.5% annual-interest loan with monthly payments for a 2900 \$/kW PV installation. This corresponds to $c^g\!=\!377.67$ This is the median loan recorded by MASSCEC and PV cost report by NREL. We multiple by 12 to convert into a yearly cost. We do not include state level incentives.
Utility functions and Demand Parameterization: We use the same methodology as in the appendix of [4], using quadratic utility functions that correspond to linear demand curves. We assume a price elasticity of -0.25 as this lies within the estimates found in [19]. We use the demand within ResStock data and an electricity price of 0.35 \$/kWh to calculate the utility function parameters as in [4].

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I. Review #157A

A. Paper summary

The paper studies how a prosumer with flexible electricity demand chooses both hourly electricity use and behind-the-meter solar PV capacity under an asymmetric tariff with different import and export prices. It develops a model showing that optimal PV investment is determined by comparing the marginal value of additional solar capacity to its annualized cost, with demand flexibility shaping that value through changes in when the customer imports, self-consumes, or exports power. The main analytical result is that changing retail prices affects customer payments not only directly, but also indirectly by shifting the optimal PV investment level. Using a Massachusetts residential case study, the authors show that time-varying and asymmetric tariffs can substantially change both PV adoption and customer bill outcomes, and that analyses holding PV capacity fixed may misstate the true effects of tariff reform.

B. Comments for authors

- The paper is framed as a study of NEM, but the payment formulation and numerical study indicate period-by-period import/export settlement. Since there is no netting across time periods, this seems closer to ”net billing” rather than ”net metering.” I think you could reframe slightly by saying the paper studies a generalized import/export tariff rather than net metering as such.
- The paper could be clearer about the (potential) issue of nonuniqueness of the optimal entry quantity. Do you encounter that in the numerical study? If so, what is the selection rule?
- The $c^g = 342$ annualized cost seems inconsistent with the $C = 375$ overnight cost in Appendix H, and I wonder if there is a typo in one of them. In the last line of Appendix H, the price should almost certainly be /kWh instead of /kW.
- There are several minor typos (repeated words, etc.) that should be fixed

C. Summarize your recommendation in one to two sentences

Overall I found the analysis to be clear, with intuitive results and a useful characterization of PV sizing incentives.

— Jacob Mays

II. Review #157B

A. Paper summary

The paper investigates the question of jointly deciding the investment and operation of a prosumer with solar under net energy metering tariffs. With a stylized model, the authors find the optimal customer response, using which they find out the optimal solar investment capacity. Then, they extend the model to consider a multi-period version.

B. Comments for authors

The paper is very lucidly written. While the math is elementary, I commend the authors for doing a clean analysis to show fairly interesting conclusions, such as the non-smooth response in investment to NEM pricing, effects of investment decisions across time that disaggregates into a direct effect and a PV effect, and the relationship of investment decision to the marginal value.

Overall, I enjoyed reading the paper a lot. My only recommendation is about future work. Consider the question of tariff changes as a result of investment and study the co-evolution of solar capacity investment together with tariff through time if possible through a simple yet illustrative model you have done in this paper.

In terms of this work, I would recommend expanding the introduction a bit to discuss industry positions and tariff structures. As it stands, that part is a bit too terse. The introduction quickly culminates into the contributions of the current paper and leads to the math model immediately.

C. Summarize your recommendation in one to two sentences

I recommend acceptance.

— Subhonmesh Bose

III. Review #157C

A. Paper summary

This paper studies joint investment and operational decisions of a prosumer under asymmetric, time-varying net metering tariffs. Unlike prior work that treats PV capacity as fixed, the authors endogenize solar investment and characterize optimal decisions via KKT conditions. They derive a marginal value condition linking optimal capacity to import, net-zero self-consumption, and export regimes (Theorem 1), and then show how capacity responds to changes in import/export prices and PV costs (Proposition 1). The analysis identifies a PV effect: tariff changes in one period affect net demand and payments in all generating periods through adjustments in optimal PV investment. A case study using simulated Massachusetts household data illustrates that ignoring endogenous PV capacity biases estimates of net demand and payment responses to tariff reforms.

B. *Comments for authors*

The paper addresses a timely policy problem with a clean theoretical framework and identifies a useful PV effect. There is still room for improvement. For instance, the analysis assumes a narrow utility specification without robustness discussion. The case study uses only a single household, and policy implications for NEM reform are not drawn concretely. That said, these issues are addressable. Below please find my detailed comments.

1) The analysis relies on a quadratic utility function (linear demand) with a fixed elasticity (-0.25). While this is a tractable choice, the paper does not discuss whether the main insights are potentially robust to other functional forms.
2) The analysis focuses on a single representative household with one set of load and PV profiles. Concerns remain about:
   - How do results vary across households with different consumption patterns, roof orientations, or demand elasticities?
   - Would the PV effect be stronger or weaker in sunnier states (e.g., California) or regions with different load-solar correlation?
   - The paper considers a single prosumer. The implications for utility cost recovery depend on aggregation across many prosumers. What would the aggregation effects be?
3) The abstract and introduction promise insights for NEM reform, but the conclusion remains somewhat generic. For example:
   - The finding that import price increases may reduce payments in some regions has direct implications for rate design. However, this paper does not offer guidance on how regulators should interpret this.
   - The asymmetry between import and export price changes suggests that export price decreases could be more effective at increasing utility revenue, but this point is not highlighted.
4) The PV effect could be more sharply contrasted with prior literature. The paper cites [10] Alahmed & Tong (2022) and [11] Chakraborty et al. (2019) for operational decisions under fixed capacity, and [12] Comello & Reichelstein (2017) for investment without flexibility. However, a direct numerical comparison would be more compelling.

C. *Summarize your recommendation in one to two sentences*

The paper can be accepted after minor changes.

— *Pengcheng You*

IV. Brief response to reviewers (optional)

We thank all three reviewers for their detailed and constructive comments. Below is a brief summary of our responses.
Reviewer 1: We clarified that our use of "net metering" encompasses all NEM variants (net billing, inflows and outflows, net feed-in), and added a footnote about this effect before equation (1). Nonuniqueness of optimal PV capacity is ruled out by strict concavity of the objective. We corrected the identified typos and repeated words throughout the manuscript.
Reviewer 2: We expanded the introduction to discuss the industry debate around NEM reform, contrasting utility and solar-industry perspectives on export compensation. We added a remark in the conclusion identifying the co-evolution of tariff design and solar investment as a promising direction for future research.
Reviewer 3: The quadratic utility function is used only in the numerical case study; the theoretical results hold for any strictly concave utility function, as the key structural insights follow from concavity and the linear tariff structure alone. Heterogeneity across households and regional solar conditions are left for future work. Aggregation is addressed via Gorman aggregation, under which the quadratic specification admits a representative consumer, justifying our single-prosumer analysis. We revised the conclusion to highlight two concrete regulatory takeaways: import price increases can have non-monotone effects on prosumer payments due to the PV effect, and export price reductions are a more reliable lever for increasing utility revenue recovery. Our current analysis includes a comparison with the fixed PV capacity case. We added a reference to [10] Alahmed & Tong (2022) and [11] Chakraborty et al. (2019) to our analysis of Figure 5 to highlight this comparison. A direct numerical comparison with fixed-demand benchmarks is deferred to future work due to the page limit constraint.

V. Brief summary of changes made to the final paper

We made four main modifications to the revised manuscript.

1) Expanded introduction. We added few sentences discussing the ongoing regulatory debate around NEM reform, contrasting the utility perspective (that symmetric NEM shifts fixed network costs onto non-solar customers) with the solar-industry perspective (that reduced export compensation negatively affect adoption incentives), and connecting this debate to the motivation for the paper.
2) Strengthened policy implications in the conclusion. We revised the conclusion to draw more concrete takeaways for regulators: first, that import price increases can have non-monotone effects on prosumer payments due to the PV effect, complicating standard rate-design intuitions; and second, that the asymmetry between import and export price sensitivities implies export price reductions are a more reliable lever for increasing utility revenue recovery. We also added a sentence identifying the co-evolution of tariff design and solar investment as a direction for future research.

3) Robustness discussion and aggregation footnote. We added a brief discussion clarifying that the main theoretical results, the marginal value condition, three-regime characterization, and PV effect, hold for any strictly concave utility function, with the quadratic form used only in the numerical case study. We also added a footnote in the case study section justifying the single-prosumer framework via Gorman aggregation. We additionally corrected all identified typos and repeated words throughout the manuscript.
4) Updated case study calibration: We revised the calibration of the case study by aligning the demand-curve calibration point with the flat, symmetric benchmark tariff. We also updated the technology cost assumptions using more recent PV installation costs and removed the ITC tax credit to maintain consistency with the retail price projections. These changes altered the numerical results, making the ”Late” tariff nearly identical to the ”Proposed” tariff. To reduce redundancy and sharpen the presentation, we removed the ”Late” tariff from the case study.