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The Hidden Impact of Prosumers and Its Fair Mitigation

Junghee Lee[1], Lai Wei[2], Ming Hu[3] and Yinliang (Ricky) Tan[4]

Abstract

We investigate the burgeoning trend of prosumers, who have transformed from traditional consumers into active renewable energy producers. While prosumers help reduce greenhouse gas emissions and reliance on fossil fuels, they often remain connected to the grid as a backup. This practice requires that utility companies reserve capacity, and conventional consumers share these associated costs. We develop a stylized model to comprehensively assess the impact of prosumers. Our findings demonstrate that, although prosumers contribute to diminishing nonrenewable energy consumption and offer potential cost savings to utility firms, they simultaneously introduce negative externalities. Specifically, they inject uncertainty into the grid, resulting in higher electricity prices and increased utility bills for regular consumers, even when fixed costs incurred by utility firms are not considered. As the intermittency of prosumer energy generation increases, the socially optimal proportion decreases while the self-selected equilibrium proportion of prosumers increases. Furthermore, we examine the potential implications of a conventional linear incentive scheme for prosumers, exemplified by the 2023 U.S. federal tax credit for solar panel installation costs. We find that such schemes may exacerbate social disparity. To address this issue, we propose a reverse-linear subsidization approach, which paradoxically requires less funding to achieve equivalent prosumer adoption rates and results in smaller social disparity.

Keywords

Prosumer, Electricity Price, Unfairness, Intervention

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1 Introduction

Recent technology advancement empowers the end users to transform themselves from passive consumers to active *prosumers*, which is a hybrid of the terms producers and consumers. Instead of consuming energy alone, prosumers can also generate electricity on their own property through solar panels, playing a key role in reducing greenhouse gas emissions and lessening the reliance on fossil fuels.

To induce more prosumers, policymakers have adopted various interventions. Starting in 2020, California is set to become the first state in the United States to require all newly built homes to install solar panels (Solar Eclipsed, 2018). Also, the United States has provided a federal solar tax credit, about 30% of the solar panel installation cost, since 2005 (Devlin, 2023). Residential solar power generation is growing rapidly worldwide. In 2017, rooftop solar installations, measured in gigawatts of capacity, were nearly ten times what they were in 2010. According to the research report by CE Delft, a leading energy consultancy company, it is estimated that nearly half of European Union citizens could produce their own renewable electricity by 2050 (Kampman et al., 2016).

One might naturally assume that renewable energy sources, like solar power, would help reduce societal utility costs. For example, the utility company may reduce fuel costs and purchase costs from the utility spot market (Satchwell et al., 2015). However, the situation in Germany may suggest

[1]Mendoza College of Business, University of Notre Dame, Notre Dame, IN, USA
[2]Antai College of Economics and Management, Shanghai Jiao Tong University, Shanghai, China
[3]Rotman School of Management, University of Toronto, Toronto, Canada
[4]China Europe International Business School, Shanghai, China

Corresponding author:
Yinliang (Ricky) Tan, China Europe International Business School, Shanghai, China.
Email: yrtan@ceibs.edu

otherwise. Hans-Josef Fell, who resides in an eco-friendly home in Germany, played a pivotal role in transforming global energy production. The solar panels he installed on his home in the 1990s initiated a massive shift toward renewable energy nationwide. By 2020, nearly half of Germany's energy came from renewable sources like solar and wind. This marked one of the most dramatic energy transitions the world has witnessed. Unfortunately, those who did not adopt renewable solutions, such as installing solar panels, experienced a spike in their electricity bills (NPR, 2020).

In late June 2021, the Pacific Northwest region of the United States, including areas such as Oregon and Washington, as well as parts of British Columbia, experienced an unprecedented heatwave that shattered temperature records. Numerous residents reported experiencing notably elevated utility bills during this time. During periods of extremely hot summers or exceptionally cold winters, electricity consumption increases sharply as people turn on air conditioners or heaters to maintain a comfortable indoor environment. To address this heightened demand, utility companies may use outdated and environmentally harmful coal and oil power plants. Some power facilities even maintain a dedicated team to ensure power supply during these peak times. Consequently, the cost of energy production can surge to four or five times its regular rate on high-demand days compared to low-demand days. This cost escalation can lead to a substantial increase in electricity bills, placing a financial strain on households with limited incomes as they contend with the elevated expenses of cooling or heating their homes.

While it is evident that prosumers play a vital role in protecting the environment, there remains an "expense" related to reserve capacity for prosumers (in addition to that of upkeeping the electrical infrastructure) that is borne by the nonprosumers. If a large number of regular consumers become prosumers, the remaining conventional consumers may bear a heavier burden of costs, even not counting the fixed costs of maintaining the electrical grid. Such a scenario has manifested in places like Germany, leading to escalated energy bills for those not producing their own energy. In this paper, we focus on the ramifications of an increasing prosumer population on traditional consumers in conjunction with a popular financial incentive to encourage more prosumers, such as a tax credit for the solar panel installation cost.

We build a stylized model to study whether energy authorities should incentivize or impose charges on prosumers and how to allocate the benefits of solar energy across the community equitably. Specifically, we focus on a utility company serving both prosumers and traditional consumers. This firm needs to decide on its internal generation capacity to maintain a regulated service level to satisfy market demand. Should total energy demand surpass this limit, the company will still meet the demand; however, any additional demand beyond its established generation capacity will come at a higher cost. This increase could be attributed to relying on less efficient energy production methods or purchasing from pricier spot markets. In the population, all consumers have heterogeneous consumption demands, and prosumers can generate electricity depending on their roof size and generation efficiency. The utility company sets a price over time that divides the cost of meeting energy needs across its consumer base, with an added fixed profit margin as sanctioned by regulations.

We obtain a set of notable results. First, given the presence of prosumers, we study the impact of their growing segments and improved solar technology on society. We demonstrate that an increase in the number of prosumers or improved conditions for renewable energy production leads to a hike in electricity prices even in the *absence* of fixed costs for the utility firm. This is due to prosumers introducing increased unpredictability into the electricity grid. Consequently, while prosumers may benefit from reduced electricity expenses, traditional consumers who are unable to become prosumers might face escalated energy costs. It is worthwhile to note that our findings hold without considering fixed costs, such as grid maintenance, that a utility firm would have, irrespective of demand (e.g., Gautier et al., 2018; Mamaghani and Çakanyildirim, 2024; Singh and Scheller-Wolf, 2022). This distinction is crucial, as it highlights the need for policymakers to account for additional factors other than fixed costs in designing interventions.

Second, we study the prosumer size in equilibrium from both social and individual perspectives, by taking into account solar panel installation costs and the social/environmental benefits of solar power generation. We characterize the conditions under which policymakers may incentivize consumers to adopt the prosumer role, beyond their own self-driven interests. These conditions underscore the contrast in different perspectives between societal interests and individual consumers' self-interested motivations. Additionally, we establish the conditions under which even if an increase in the number of prosumers raises the electricity price, potentially leading to a death spiral, the prosumer size in equilibrium remains stable. This stability is also maintained when policymakers introduce economic incentives to encourage greater solar panel adoption.

Third, should policymakers aim to promote greater solar panel adoption, we show that offering subsidies based on roof size can achieve the desired prosumer level. A common policy, such as the federal tax credit for solar panel installation in 2023 in the United States (Department of Energy, 2023), can effectively increase the number of prosumers. However, this comes at the cost of equity, as it primarily benefits individuals who may need less financial support. To address this fairness issue, we suggest a feed-in tariff scheme in which the subsidy for solar panels decreases as roof size increases and show that a lesser financial burden is placed on regular consumers, compared to the subsidy proportional to roof size. That is, our proposed subsidy achieves the socially optimal number of prosumers and mitigates unfairness concerns between prosumers and consumers.

Subsequently, we expand our base model into five extensions. First, we investigate a complex yet more practical scenario of net metering in which prosumers can sell their excess energy back to the grid at a certain rate. Our findings indicate that such a practice cannot simultaneously achieve the socially optimal prosumer level and mitigate unfairness. However, our proposed approach can achieve both objectives. Second, we explore a situation in which the utility firm charges contingent prices after all intermittencies have become realized and demonstrate that the difference between the main and alternative pricing mechanisms is reasonably small to preserve the primary insights. Third, we incorporate a consumer group referred to as green consumers, who may earn intangible benefits in addition to financial gain from renewable energy generation. We find that unfairness among green consumers is less than that among regular consumers, implying that unfairness between consumers and prosumers is smaller with more green consumers. Fourth, we take an egalitarian approach and aim to achieve equity between the two consumer segments, that is, prosumers and regular consumers, by maximizing their minimum utility levels. We show that the egalitarian fairness proportion behaves like socially optimal and self-interested equilibrium proportions when renewable energy generation efficiency and affordability improve. Nevertheless, as generation intermittency among prosumers increases, the egalitarian fairness proportion increases like the self-interested equilibrium proportion, while the optimal proportion for the social cost decreases contrastingly. Finally, we investigate independent demand patterns of the roof size and illustrate that the main result of prosumers' negative externality on utility prices from the base model remains unchanged.

2 Literature Review

Our study is related to the Operations Management (OM) literature on (i) environment and sustainability and (ii) renewable energy, but it also deviates from the existing literature in some essential aspects.

2.1 Environment and Sustainability

Researchers in OM have explored various environmental and sustainability-related topics. In-depth reviews on these topics can be found in Girotra and Netessine (2013) and Agrawal et al. (2019). Generally, two approaches emerge: One focuses on mitigating undesirable activities by firms (such as the use of child labor or violations of environmental standards), while the other encourages desirable activities, such as the adoption of green technologies by firms or the purchase of electric vehicles by consumers. The latter stream of literature aligns with our research, since our primary research question is the adoption of green technology, specifically rooftop solar panels. For example, Cohen et al. (2016) uncover the importance of demand uncertainty in designing consumer subsidies for firms' green technology. In a related vein, Krass et al. (2013) study how regulators may use tax, subsidy, and rebate levels to influence a firm's choice in green technologies, and Ma et al. (2019) study when to subsidize products and/or service infrastructure for clean technology. Raz and Ovchinnikov (2015) study government interventions like subsidies (or taxes) and rebates to encourage consumption of public interest goods such as electric vehicles, where interventions do not vary across consumers. Our study connects with research on competition-induced operational uncertainty. Ovchinnikov et al. (2023) show that inventory risk from competitive uncertainty can paradoxically raise market prices. Similarly, utilities facing intermittency from prosumers' renewable generation experience analogous risks, highlighting how operational uncertainty broadly impacts market outcomes.

However, our approach differentiates itself by investigating the consumer's decision, that is, whether to become a prosumer rather than the firm's decision. Furthermore, we emphasize that the seemingly desirable choice of becoming prosumers by installing solar panels may impose unintended negative externalities on society. In light of this, we analyze the trade-off associated with prosumers and propose a *fair* mechanism to achieve a socially optimal level of technology adoption.

2.2 Renewable Energy

This paper is also related to the literature on renewable energy. The supply of electricity from these renewable sources is intermittent due to weather conditions, air pollution, and other determinants in the environmental conditions. Hu et al. (2015) study the capacity investment problem of renewable energy technology. They illustrate that data granularity is an important decision factor, as the coarse data may not well reflect the intermittency of the renewable generation. Alizamir et al. (2016) study the optimal design of the feed-in-tariff (FIT) policies. Under the FIT policy, governments purchase renewable energy at tariffs that are set above the market price, aiming to foster learning and accelerate the diffusion of renewable energy. The authors find that the current constant profitability mechanism is rarely optimal and propose some alternative ones to improve the efficiency of the FIT policy. Aflaki and Netessine (2017) examine the effect of carbon taxes on the cost and share of renewable energy capacity in an energy portfolio. They show that higher carbon prices may discourage investments in renewable energy capacity. Al-Gwaiz et al. (2017) find that the policy of economically curtailing the intermittent generation from renewable energy sources can intensify market competition, reduce price volatility, and improve the system's overall efficiency. Kök et al. (2015) compare the flat pricing and peak pricing on the investment levels of renewable and conventional energy sources. They suggest that flat pricing can lead to lower carbon emissions and a higher consumer surplus than peak pricing. Considering a day-ahead electricity market comprising both conventional and renewable firms, Sunar and Birge (2019) show that imposing a penalty rate can result in larger renewable energy commitment in the day-ahead market. Leveraging an infinite-horizon, continuous-time model, Angelus (2021) characterizes the consumers' optimal investment decisions for standalone small-scale renewable energy sources. Interested readers in this topic should refer to Parker et al. (2019) for comprehensive reviews regarding renewable integration and other topics in the electric power industry.

It is worthwhile to point out that there are several studies looking into solar energy in particular. In the nonresidential solar energy market, companies often choose between direct ownership and working with a service provider through third-party ownership. Through an empirical study, Guajardo (2018) shows that third-party ownership can outperform direct ownership by 4% in terms of production yield. To encourage more adoption of renewable generation, policymakers often provide financial incentives. Agrawal et al. (2022) focus on the nonownership business models in the solar power market, where a solar power company incurs the installation cost with ownership, and the customer may pay either a fixed leasing fee or per-unit price. The authors find that a higher investment subsidy may backfire, leading to lower total adoption and generation. In contrast, Babich et al. (2020) compare the impacts of the FIT policy and the tax-rebate policy on consumers' adoption decisions. The authors characterize the conditions that favor the FIT vs. the tax-rebate policy. However, both papers do not consider fairness concerns arising for regular consumers vs. prosumers.

A growing body of literature explores the relationship between prosumer adoption and electricity prices. One stream finds that increased penetration of prosumers can reduce prices due to the near-zero marginal cost of renewables, which displace costlier fossil fuel generators in the merit order (Würzburg et al., 2013). Renewables also provide a hedging function against fossil fuel price volatility, contributing to price stabilization (Navia Simon and Diaz Anadon, 2025). In contrast, the other stream of literature emphasizes that more prosumers raise the electricity price, creating fairness concerns. It is often attributed to the reallocation of grid maintenance cost (Cai et al., 2013; Costello and Hemphill, 2014; Kuznetsova and Anjos, 2020) and transmission and distribution cost (Gautier et al., 2018). That is, the primary driver of price hikes is the increased burdens of sharing fixed costs among reduced consumers. Consequently, various policy interventions were proposed to address fair distribution of fixed cost. Gautier et al. (2018) compare two pricing mechanisms (net metering and net purchasing) as unfairness mitigation measures with fixed cost. As consumers have to use such mechanisms regularly, the actual performance depends on the day-to-day realization of intermittency, which is excluded. Singh and Scheller-Wolf (2022) explore the tariff structure to minimize such fairness issues but abstract away the utility firm's capacity decision. They show that if every consumer pays the uniform variable energy price irrespective of their type but prosumers pay an additional fixed fee, society can alleviate the unfairness between regular consumers and prosumers. Mamaghani and Çakanyildirim (2024) propose a similar mechanism, the buyback price and a subscription fee, to mitigate the utility death spiral, where electricity prices increase with more prosumers. However, the allocation of fixed costs represents only one dimension of the trade-offs introduced by prosumers. There is a trade-off regarding the impact of prosumers on the electricity grid. On the one hand, the increased adoption of prosumers can amplify demand volatility due to the intermittency of renewable energy sources (e.g., Cordera et al., 2023; Wu and Kapuscinski, 2013), creating risks for the grid, similar to the competition-induced inventory risks discussed by Ovchinnikov et al. (2023). On the other hand, prosumers' energy generation helps reduce peak demand, which enables utility firms to lower their capacity costs. Satchwell et al. (2015) note that prosumers can reduce generation costs because the utility firm can reduce fuel costs and purchased power costs, and defer utility generation investments. This inherent trade-off makes it ambiguous whether prosumers indeed increase the electricity price if fixed cost factors are excluded.

Motivated by these papers, our study complements this stream of literature by considering financial incentives for installation and fairness simultaneously in distributed solar power generation. We endogenize the utility firm's operational decisions in the absence of fixed costs and theoretically show that the electricity price can rise even without fixed costs. This finding underscores that, despite fair-sharing policies for fixed costs, the utility firm may still increase prices as the proportion of prosumers grows, which should be accounted for when designing interventions. Our analysis provides critical insights into the broader implications of prosumer adoption for generation capacity, electricity pricing, and social fairness.

3 The Model

In this study, we consider a utility firm that provides electricity to a group of consumers, a proportion of whom can generate electricity through their own renewable energy facilities. We first describe the consumers and the electricity provider, followed by their decision sequence.

3.1 Consumers

Traditionally, the centralized energy model is the norm in which consumers can only purchase electricity from the grid. However, due to the rise of renewable energy technology, consumers installing solar panels on their rooftops can consume the generated energy and may sell the rest back to the grid. This type of consumer is commonly known as the prosumer, who both consumes and produces energy. Without loss of generality, we normalize the total market size to be a unit.

A prosumer's generation output depends on various factors, such as the size of solar panels and the amount of sunlight. We first let a consumer's roof size s be uniformly distributed between 0 and 1, in which 0 reflects no physical space for solar panels (i.e., high-rise apartment building) and 1 reflects the other extreme.[1] Next, we model inherent intermittency from environmental conditions, denoted as ξ. To capture this variability in the prosumer's generation output parsimoniously, we assume that the electricity output from a prosumer with the roof size s is $g = s \cdot \xi$. We assume that ξ follows a uniform distribution between $\mu - \sigma$ and $\mu + \sigma$, where σ represents the amount of intermittency from weather and μ represents the expected efficiency of a unit solar panel. Since the generation cannot be negative, we assume $\mu - \sigma > 0$ henceforth. This approach implies that consumers reside within close proximity and share similar weather conditions. Although our model does not fully incorporate multiple geographical areas where weather is correlated, the model still provides valuable insights. When there are multiple intermittencies with correlation, the aggregated intermittency would matter to the utility firm's business decisions, such as capacity and pricing. Thus, if we interpret the current σ as the aggregated intermittency, our model approximately captures the impact of prosumers across various geographical areas on the utility firm's decision.

Regarding consumer demand, electricity consumption is relatively stable compared to renewable energy generation. For example, people still need to consume electricity on a rainy day when solar panels hardly generate any electricity. To represent the relative stability of electricity consumption, we adopt deterministic demand following the literature (e.g., Singh and Scheller-Wolf, 2022). However, electricity consumption may vary across consumers, depending on various factors such as the house's efficiency, heating technology, and overall energy consumption patterns, as well as socioeconomic factors. To capture such heterogeneity and ensure analytical tractability, we assume that the electricity consumption is linearly increasing in the roof size s with rate d (e.g., Singh and Scheller-Wolf, 2022). That is, our model is most valid when the roof size is the primary factor for the electricity consumption. However, if the consumption varies little across roof sizes or is random and independent of roof size, our results may not hold. Therefore, to verify the robustness of the results, we investigate two scenarios: (1) The demand is deterministic but independent of the roof size, and (2) the demand is random in Section 5.5.

We define γ as the proportion of prosumers. The remaining proportion $(1 - \gamma)$ represents regular consumers who do not have solar panels. Thus, the aggregated demand of both regular consumers and prosumers is a function of γ. We define such aggregated demand that the utility firm should satisfy as $D_u(\gamma)$, which can be interpreted as the net demand (total demand minus prosumer's generation) to the utility firm.

We first analyze the scenario where γ is exogenously given in order to examine the interaction between prosumers and the electricity price. Since the renewable energy generation equipment is costly to install, we later introduce the fixed and variable installation costs of solar panel systems, I_0 and I, respectively, to study the equilibrium outcomes based on consumers' endogenous decisions on becoming a prosumer or not.

3.2 The Utility Firm

The utility firm has two sources of capacity, internal and external, to serve consumer demand. In practice, there are multiple internal generation facilities with varying flexibility. The utility firm follows merit order dispatch rules to determine which source to utilize. For example, it utilizes a low-cost but inflexible source, such as nuclear power, first to satisfy the demand and then gradually moves on to more expensive and flexible sources, like natural gas. To focus on the uncertain demand driven by prosumers, we assume that the firm utilizes the inflexible source to satisfy the minimum demand and the fully flexible source to serve the rest. Without loss of generality, we normalize the minimum demand to zero.

We consider that the utility firm has two sources for electricity; (1) an internal and fully flexible generation capacity and (2) a spot (wholesale) market. Let c and C denote the unit costs for the internal and external sources, respectively. While the spot market price is volatile, its expected price is commonly assumed to be greater than the firm's internal generation cost (e.g., Sunar and Swaminathan, 2021), leading to $c < C$.

In one extreme case, the utility firm can serve the market without any internal capacity. Nevertheless, utilities in a regulated market are required to be vertically integrated, that is, to own generation capacity (Environmental Protection Agency, 2025). Moreover, relying on a sole source would be more vulnerable for the reliable provision of electricity. Therefore, we model that the firm has a predetermined service level, β, with the internal capacity. We define $Q(\gamma)$ as the internal and fully flexible generation capacity for some γ. Then, the relationship between β and $Q(\gamma)$ can be expressed as $Prob(D_u(\gamma) \leq Q(\gamma)) = \beta$. With its planned internal generation capacity $Q(\gamma)$, the total expected generation cost TC is as follows:

$$TC(Q(\gamma)) = c_0 \cdot Q(\gamma) + c \cdot E[\min\{D_u(\gamma), Q(\gamma)\}] + C \cdot E[(D_u(\gamma) - Q(\gamma))^+], \qquad (1)$$

where c_0 is the unit capacity building cost and $(\cdot)^+ = \max(\cdot, 0)$. While β is an exogenous parameter, γ depends on other parameters like μ, σ, etc. As our research questions focus more on characteristics about solar panels such as efficiency, intermittency, and affordability than β, we use $Q(\gamma)$ instead of $Q(\beta, \gamma(\mu, \sigma))$ for ease of exposition. Also, if c_0 is zero, TC in (1) reflects the sum of all the variable costs.

In most parts of the United States, there is a single electricity supplier in the local market. A regional government allows the utility firm to be a monopoly in return for stable electricity provision at a reasonable price. The firm can determine most of its business decisions but is regulated for pricing. Public utilities commissions in most U.S. states regulate electricity prices. In Canada, electricity price is primarily under provincial jurisdiction. For example, the Ontario Energy Board sets the electricity rate annually (Ontario Energy Board, 2025). In Mexico, the role of state companies is increasingly dominant

(Barrera, 2025). Because the utility firm is a for-profit organization, these agencies regulate the utility price to enable the firm to operate with some profit margin. We define m as a certain profit margin in addition to its cost. As a result, the price can be expressed as follows:

$$p(\gamma) = \frac{TC(Q(\gamma))}{E[D_u(\gamma)]} + m. \tag{2}$$

Without loss of generality, we assume that the utility firm's unit electricity price is set to break even, that is, $m = 0$.

3.3 Decision Sequence

It is often the case that consumers choose to install solar panels when the potential economic benefit is sufficiently large (Cohen, 2023). As the economic benefit is contingent on the electricity price, consumers should anticipate how the utility firm would operate in general and how the electricity price would change in particular.

The electricity price results from the utility firm's capacity, costs, and overall demand. While utility firms regulated by the local governments are typically required to report long-term strategic plans, called Integrated Resource Plans (IRPs), IRPs do not have detailed operations plans to achieve particular goals due to their strategic nature. In contrast, the utility firms set up mid- to short-term detailed plans for operating their power generation facilities. If the firm cannot set up its plan properly, it will waste the internal generation resources or rely heavily on the more expensive external market, increasing the total expected cost. To avoid such unnecessary waste, the firm should determine the internal capacity carefully so that its proposed electricity price is approved by regulatory agencies such as a state public utility commission. Thus, we incorporate the firm's internal capacity decision into the model (cf. Singh and Scheller-Wolf, 2022; Sunar and Swaminathan, 2021).

To reflect the strategic decision of prosumers to install solar panels and the operational-level decision by the utility firm of setting up and adjusting capacity, we model that consumers first determine whether to install the solar panels and become prosumers, in anticipation of the electricity price. Next, given the consumer market composition, that is, the proportion of the prosumers (γ) and the anticipated demand pattern/distribution, the utility firm sets up how much to generate (e.g., gigawatt hours) using the internal facilities (Q) under the predetermined portion (β). Finally, the expected electricity price (p) is set to give the firm a unit profit margin of m. Figure 1 illustrates the sequence of events.

As the prosumers' strategic decisions of installing solar panels are more long-term than the utility firm's capacity decision at the operational level, we first analyze the utility firm's decision with a given proportion of prosumers γ. Then, we endogenize the consumers' decisions to become a prosumer in our model. For convenience, we summarize the notation used in this study in Table EC.1 of the Appendix.

4 Analysis

We start our analysis by investigating how the price and generation capacity are determined for a given fraction of prosumers. In doing so, we focus on the case where the demand is greater than the prosumer's renewable generation in this section, that is, $d > \mu + \sigma$, to provide clear insights. This is rather innocuous as the ratio of small-scale solar photovoltaic generation with respect to the use of electricity by residential customers is about 2.6%[2] in 2022. Yet, we explore the rest of the cases and verify that our main insights remain valid in Section 5.1.

Based on the pricing mechanism, we derive two different proportions of prosumers of interest: (1) The proportion via consumers' self-selection and (2) the proportion minimizing the total social cost. We conclude the section with two intervention mechanisms to achieve the total cost-minimizing proportion via self-selection.

4.1 Generation Capacity and Electricity Price

We use backward induction to derive the equilibrium outcomes. Notice that the pricing decision in Stage 3 is governed by (2). Anticipating this, the firm should set the internal capacity to meet the service level constraint in Stage 2. While the electricity consumption is assumed to be deterministic, the electricity demand to the utility firm is random due to intermittent generation of prosumers. Because of the installation costs (fixed and variable), not all consumers find it beneficial to be prosumers. A house with a larger roof size incurs less average installation cost and finds it more economical to be a prosumer compared to that with a smaller roof size.

As the consumer's roof size is continuous, there is a threshold roof size, saying $\hat{s}$ such that those whose roof size is greater than $\hat{s}$ become prosumers. Since the roof size is assumed to be uniformly distributed between 0 and 1, the portion of prosumers is $1 - \hat{s} \triangleq \gamma$. We will formally prove this claim in Lemma 2. As a result, the aggregate demand for the utility firm can be expressed as follows:

$$\begin{aligned} D_u(\xi|\gamma) &= \int_0^{1-\gamma} (d \cdot s) ds + \int_{1-\gamma}^{1} (d \cdot s - \xi \cdot s) ds \\ &= \frac{1}{2}d - \frac{1}{2}\xi(2\gamma - \gamma^2). \end{aligned} \tag{3}$$

Since ξ is a uniform random variable affecting the demand, $D_u(\xi|\gamma)$ is also a uniform random variable between $D_u(\mu+\sigma|\gamma)$ and $D_u(\mu-\sigma|\gamma)$. Recall that the firm should achieve the service level β with its internal capacity, that is, $P(D_u(\xi|\gamma) \le Q^*) = \beta$. Then,

$$Q^* = 2E[D_u(\xi)] - (1-\beta)D_u(\mu - \sigma) - \beta D_u(\mu + \sigma).$$

As the utility firm determines the price following (2), we replace Q with Q^* in (1), compute (2), and derive the following proposition.

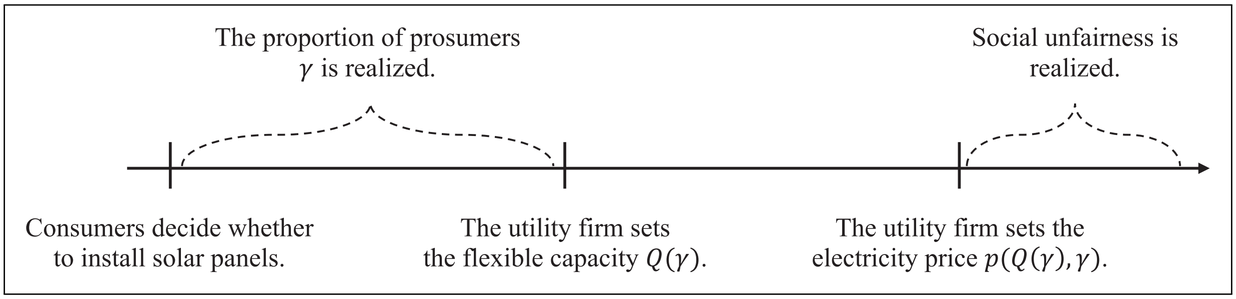

Figure 1. Sequence of events.

PROPOSITION 1. *For given β and γ, the electricity price is*

$$\begin{aligned} p(Q^*(\gamma), \gamma) &= c_0 + c + \frac{(C-c)(1-\beta)^2 + c_0(2\beta-1)}{d-\mu(2\gamma-\gamma^2)}\sigma(2\gamma-\gamma^2) \quad (4) \\ &= c_0 + c + \sqrt{3}\left((C-c)(1-\beta)^2 + c_0(2\beta-1)\right) CV_u, \quad (5) \end{aligned}$$

where $E[D_u] = \frac{1}{2}d - \frac{1}{2}\mu(2\gamma-\gamma^2)$, $\sigma_{D_u} = \frac{\sigma}{2\sqrt{3}}(2\gamma-\gamma^2)$, and $CV_u = \frac{\sigma_{D_u}}{E[D_u]}$. Moreover,

(i) *While the internal capacity decrease in γ and μ, it increases in σ if and only if $\beta > \frac{1}{2}$.*
(ii) *The electricity price increases in γ, μ, and σ regardless of the capacity cost (c_0) if $\beta > \frac{1}{2}$.*

All proofs throughout the paper are relegated to the Online Appendix. Proposition 1(i) shows that if the required service level using internal generation (β) is high enough ($\beta > 1/2$), the firm should reduce its generation capability when there are more prosumers (γ) or the prosumers' mean energy generation output (μ) increases. The impact of intermittency (σ) is less straightforward. When β is high enough ($\beta > 1/2$), the firm should increase its internal generation capability as σ increases. Otherwise, the optimal internal capacity decreases in σ.

Despite lower capacity cost due to more prosumers, Proposition 1(ii) implies that the electricity price still increases in γ, which leads to a negative externality for regular consumers. This result suggests that even though the firm requires less output when there are more prosumers, the electricity price will actually be higher. This is because prosumers' electricity generation inherently has intermittency and burdens the utility firm's operations. To discuss the effect of γ more clearly, we utilize (5). It is evident that $E[D_u]$ is decreasing in γ, but σ_{D_u} is increasing in γ. Therefore, the coefficient of variation (CV_u) becomes larger, leading to an increase in the price.[3] In other words, more prosumers will reduce the net demand for utility, which brings down the utility firm's internal generation capacity in equilibrium. Because the utility firm is required to keep a relatively high service level, it reduces the generation capacity slower than the demand, suggesting that per unit price for internal generation capacity ($Q/E[D_u]$) increases. Moreover, in case of high demand, the amount of electricity purchased from the external source becomes greater ($C \cdot E[(D_u - Q^*)^+]$). The combination of these two effects drives the price up when facing a larger fraction of prosumers γ. The price will also become higher despite more favorable conditions for renewable energy generation, such as improved generation efficiency and more sunlight, that is, a higher μ. While a higher μ increases the total renewable energy generation like a higher γ, it does not affect σ_{D_u} but only reduces $E[D_u]$, increasing $p(Q^*(\gamma), \gamma)$.

There are divergent findings regarding the relationship between the electricity price and prosumers. One stream of literature argues that growing prosumers can lower the electricity price. Since solar and wind have near-zero marginal cost, their entry can push more expensive fuel-based generators out of the dispatch order, reducing the market-clearing price, referred to as "merit-order effect" (Würzburg et al., 2013). This can translate to cheaper wholesale electricity during windy or sunny periods. If these savings are passed through, consumers could see lower or stabilized prices. Renewables can also hedge against volatile fossil fuel prices, providing an "insurance value" by reducing dependence on fuel price spikes. Recent simulations of Europe's power market in 2030 show that higher renewable shares would significantly stabilize prices and dampen the impact of gas price surges, yielding social welfare gains (Navia Simon and Diaz Anadon, 2025). These arguments require assumptions that the focus is on the short term, where the fixed installation costs are not factored in, and the short-term savings due to lower or more stabilized prices are passed through to the consumers, which may not be the case in practice.

In contrast, the other stream finds an increasing price in prosumers with different reasons, such as reallocation of grid maintenance cost (Cai et al., 2013; Costello and Hemphill, 2014; Mamaghani and Çakanyildirim, 2024) and transmission and distribution cost (Gautier et al., 2018). In short, the primary driver of price increases is the increased burdens of sharing fixed costs among reduced consumers. As a result, it is common to implement policies to tackle fair distribution of fixed cost (e.g., Gautier et al., 2018; Mamaghani and Çakanyildirim, 2024). However, we show that the electricity price can still increase without any fixed cost (e.g., c_0). This finding provides an important insight for policymakers: They should consider the negative externalities from prosumers due to intermittent generation for interventions, in addition to fixed costs.

4.2 Optimal Proportions of Prosumers

We have analyzed how the utility firm responds to a given proportion of prosumers. In this subsection, we endogenize the proportion of prosumers by allowing consumers to choose whether to become prosumers. Specifically, consumers may weigh the benefits, such as the amount of savings on their electricity bill, against a sizable installation cost. At the same time, the policymakers may also be interested in influencing these decisions, as they should consider more aspects of renewable energy generation than an individual prosumer.

In what follows, we introduce the installation costs for solar panels and their social benefits. For the former, we consider both fixed and variable installation costs. Variable costs can be thought of as the unit solar panel price and the average per-square-foot installation cost. Fixed costs capture the fact that not everyone can be a prosumer due to physical restrictions. For the latter, it incorporates the environmental benefits of clean air, mitigated climate change, and the strategic benefits from reduced reliance on imported resources. For tractability, we do not distinguish the sources of the social benefits associated with having more prosumers in the market. With this setting, we analyze two different optimal proportions of prosumers, one from the policymaker's perspective and the other from the consumers' perspective.

To begin with, we suppose that a policymaker is interested in minimizing the total social cost, defined as the sum of the utility firm's electricity generation cost and the prosumers' installation cost, subtracting any social benefits thanks to solar panels. We recognize that individuals can also enjoy social benefits and consider them for their own decisions, which may differ from those of policymakers. To model it parsimoniously and without loss of generality, we set an individual's social benefit from solar panels to zero. Then, we introduce a parameter α that captures the difference between the social and individual benefits from installing solar panels. For example, if $\alpha > 0$ ($\alpha < 0$), the society appreciates more (less) than an individual by α per unit solar panel. Thus, the total social cost is

$$\begin{aligned} F_T(\gamma) &= TC(Q^*(\gamma)) + \int_{1-\gamma}^{1} (Is + I_0)\, ds - \int_{1-\gamma}^{1} \alpha s\, ds \\ &= c_0 \cdot Q^*(\gamma) + c \cdot E[\min\{D_u(\gamma), Q^*(\gamma)\}] \\ &\quad + C \cdot E[(D_u(\gamma) - Q^*(\gamma))^+] + \frac{1}{2}(I - \alpha)(2\gamma - \gamma^2) \\ &\quad + I_0\gamma, \end{aligned} \tag{6}$$

where I_0 and I are the fixed and the variable installation costs. We characterize the socially optimal proportion of prosumers in the following lemma.

LEMMA 1. *Let γ_c^* be the optimal proportion of prosumers that minimizes the total cost $F_T(\gamma)$. If $\alpha > I_0 + I - c\mu - c_0\mu + (C - c)\sigma(1-\beta)^2 + c_0\sigma(2\beta - 1)$, there exists $\gamma_c^* \in (0, 1]$ defined in (EC.5). Otherwise, $\gamma_c^* = 0$ and $p(\gamma_c^*) = c_0 + c$.*

Lemma 1 shows that if the installation cost is too high, or equivalently, the differential social benefit (α) is too small, having any prosumers will increase the total social cost. Otherwise, there is a positive optimal prosumer level γ_c^* for the society. As the paper focuses on the impact of prosumers, we focus on the more interesting case of $\gamma_c^* > 0$ henceforth.

Next, we explore the optimal fraction of prosumers if the policymaker does not adopt any interventions and each consumer decides whether to become a prosumer by weighing the installation cost vs. the savings from the electricity bill. Suppose that there is γ proportion of prosumers, and the corresponding electricity price is $p(\gamma)$. For a normal consumer with roof size s, if she becomes a prosumer, she can save the amount of $p(\gamma) \cdot \mu \cdot s$ from the electricity bill but needs to incur $I \cdot s + I_0$ for the installation cost of solar panels. As her environmental benefits of being a prosumer are normalized to zero, her net benefit can be written as $g(s, \gamma) \triangleq (p(\gamma) * \mu - I) * s - I_0$ for some γ. It is beneficial for her to become a prosumer if and only if $g(s, \gamma) \geq 0$. Then, the proportion of prosumers γ_d resulting from the consumers' rational decisions solves $g(1-\gamma_d, \gamma_d) = 0$. That is, the consumers with roof sizes smaller than $1 - \gamma_d$ remain as normal consumers ($g(s, \gamma_d) < 0$ for $s < 1 - \gamma_d$), while the consumers with roof sizes larger than $1 - \gamma_d$ will choose to become prosumers ($g(s, \gamma_d) > 0$ for $s > 1 - \gamma_d$). The next lemma shows that there exists a unique proportion of prosumers via consumer self-selection.

LEMMA 2. *Define $G(x) := g(x, 1-x) = (p(1-x) \cdot \mu - I) \cdot x - I_0$. If $(c+c_0)\mu > I + I_0$, there exists a unique and stable equilibrium $\gamma_d^* \in (0, 1)$ such that $G(1 - \gamma_d^*) = 0$.*[4]

It is important to note that γ_d^* represents a stable equilibrium. Although higher electricity prices make prosumer adoption more attractive, leading to a reinforcing mechanism, the adoption process stops at γ_d^*, avoiding a utility death spiral. This stability arises from consumer heterogeneity in roof sizes, which translates into differing installation costs and benefits.

To illustrate this, consider a sequential decision-making process. Initially, with no prosumers, the consumer with the largest roof finds it optimal to adopt, triggering a marginal increase in electricity price. The next consumer, with the second-largest roof, also finds adoption beneficial and becomes a prosumer, further raising the price. This process continues until a consumer with the roof size of γ_d^*. Those with smaller roofs than γ_d^* would not find the benefit of being a prosumer sufficient, and solar panel adoption ceases.[5]

We have characterized two optimal proportions of prosumers: The optimal proportion minimizing the social cost (γ_c) and the equilibrium proportion based on consumers' self-selection (γ_d). Then, how do they compare? Do they exhibit similar features? The following proposition sheds light on these questions.

PROPOSITION 2. *Suppose that the demand is sufficiently higher than the average solar panel generation ($d > \frac{4}{3}\mu$).*

(i) *There exists an $\alpha_0 > 0$ such that $\gamma_c^* \leq \gamma_d^*$ for $\alpha \leq \alpha_0$ and $\gamma_c^* > \gamma_d^*$ for $\alpha > \alpha_0$.*
(ii) *Both the optimal and equilibrium proportions of prosumers are decreasing in the installation cost (I or I_0) and increasing in the renewable energy generation efficiency (μ).*
(iii) *Although the socially optimal proportion (γ_c^*) is decreasing in the renewable energy generation intermittency (σ), the equilibrium proportion via consumers' self-selection (γ_d^*) is increasing in σ.*

Recall that α represents the differential benefit that society as a whole enjoys over an individual. Proposition 2(i) shows that if such differential benefits are large enough, the policymakers would like to encourage more solar panel adoption by having more prosumers than the self-selection equilibrium amount. It is well aligned with the major policies in various developed countries (e.g., the Inflation Reduction Act of 2022 in the United States). In contrast, if society does not recognize such a high α, then more regular consumers are willing to adopt solar panels than what the policymaker desires.

Proposition 2(ii) shows that there are similarities between the socially optimal and self-selection equilibrium proportions of prosumers: As the renewable energy generation becomes more efficient (a higher μ) and affordable (a lower I or I_0), having more prosumers is preferred regardless of the perspectives. Figure 2(a) illustrates that both the solid and the dashed lines are decreasing in the variable installation cost I, representing γ_c^* and γ_d^*, respectively. As solar panels are more affordable (e.g., I is decreasing), Figure 2(b) shows that the electricity price is increasing.

However, Proposition 2(iii) shows a stark contrast between the two proportions. High intermittency means that the prosumers' generation is sometimes substantially low. Because the prosumers still rely on the utility firm, the firm should be prepared for such a scenario with enough generation capacity, resulting in a greater total cost and a higher electricity price. To minimize the total cost, fewer prosumers are preferred. Ironically, such a high price motivates more regular consumers to become prosumers. Figure 2(c) illustrates this contrast with a decreasing solid and an increasing dashed line. It is worthwhile to note that the electricity price increases despite fewer prosumers, as illustrated in Figure 2(d) with the solid line. This is because the optimal price is simultaneously affected by both γ and σ according to (5). The increasing price implies that the direct effect of σ is greater than its indirect effect via γ. This phenomenon mirrors inventory risk in other operational contexts, where firms manage uncertainty in demand and competition, leading to higher market prices (Ovchinnikov et al., 2023). Similarly, utilities face operational uncertainty from prosumers' intermittent renewable energy generation, prompting higher electricity prices.

4.3 Interventions for the Socially Preferred Proportion of Prosumers

We have shown that the equilibrium and optimal proportion of prosumers can differ for individuals and society. Policymakers may influence individuals with proper interventions, such as adjusting the installation cost. However, this naive approach leads to a natural question: What if policymakers need extra funds to subsidize solar panel adoptions or have an extra surplus by levying a tax on prosumers? There is a spectrum of approaches regarding government subsidies. On one end, researchers assume that there is no financial limit on the total subsidy (e.g., Ma et al., 2019). On the other end, they assume a fixed amount of the total subsidy because of a limited budget (e.g., Arora et al., 2021). In what follows, we propose a simple yet budget-neutral mechanism that achieves the socially preferred proportion of prosumers (γ_c^*) via self-selection.[6]

For the intervention to be budget-neutral, the policymakers need two levers, one for prosumers and the other for regular consumers. We let I_d and θ represent such levers for prosumers and regular consumers, respectively. In particular, I_d is the government subsidy ($I_d < 0$) or tax ($I_d > 0$) for each solar panel. Similarly, θ is a subsidy ($\theta > 0$) or tax ($\theta < 0$) for consumers' electricity usage per unit. When the electricity price is $p(\gamma)$, a regular consumer with roof size s uses $d \cdot s$ and pays $(p(\gamma) - \theta) \cdot d \cdot s$ for her electricity usages. If she becomes a prosumer, she saves $p(\gamma) \cdot \mu \cdot s$ on average but needs to incur the solar panel installation cost $(I + I_d) \cdot s + I_0$. Thus, her net saving for a given price $p(\gamma)$ is $(p(\gamma)\mu - I - I_d - \theta d) \cdot s - I_0 =: g_d(s, \gamma)$. Compared to the net saving without any intervention $g(s, \gamma)$, $g_d(s, \gamma)$ has the extra term of $-(I_d + \theta d)s$ due to the intervention. If this term is negative, $g_d(s, \gamma)$ is larger, implying that there are more incentives to be a prosumer. In general, policymakers may want to decrease or increase the proportion of prosumers. As most policymakers are interested in having more prosumers, we focus on the scenario where $\gamma_d^* < \gamma_c^*$ from now on.[7] The next proposition characterizes the intervention (I_d, θ) that induces the social optimal via self-selection.

PROPOSITION 3. *Suppose that the policymakers want to induce more solar panel adoption, that is, $\gamma_d^* < \gamma_c^*$. Define $I_d = (1-\gamma_c^*)^2 \left\{ \frac{d}{d-\mu[2\gamma_c^* - (\gamma_c^*)^2]}[(C-c)(1-\beta)^2 + c_0(2\beta - 1)]\sigma - \alpha \right\}$ and $\theta = \frac{\gamma_c^*(2-\gamma_c^*)}{d(1-\gamma_c^*)^2} I_d$. The intervention ($I_d$, θ) is budget-neutral and results in the proportion of prosumers via self-selection equal to the socially preferred proportion of prosumers, that is, $\gamma_{d,s}^* = \gamma_c^* > 0$.*

The intervention is simple in its structure; the size of the intervention is proportional to the roof size, θ is proportional to I_d, and their signs are identical for the intervention to be

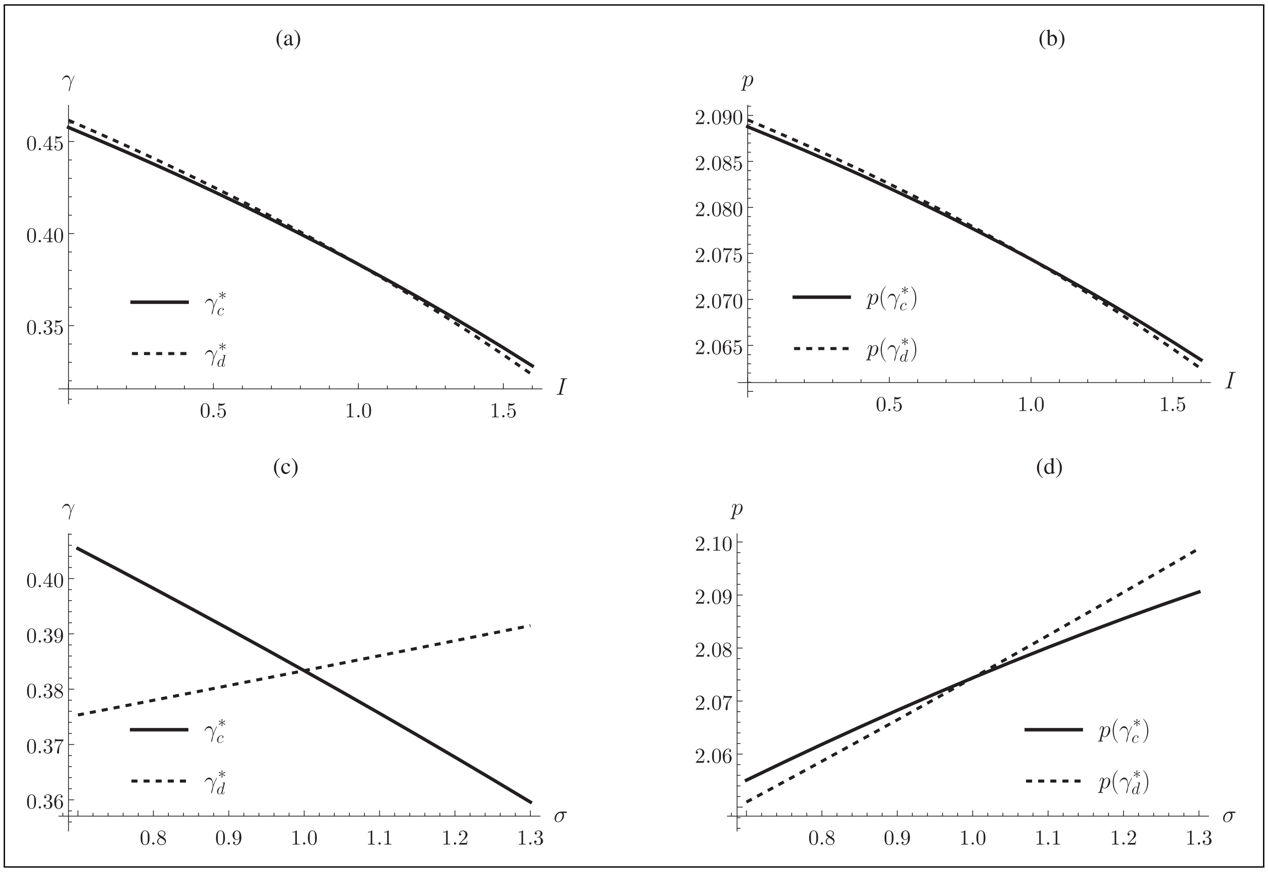

Figure 2. The comparisons of the optimal proportion of prosumers and the electricity price. (a) Optimal proportions of prosumers vs. I; (b) optimal price vs. I; (c) optimal proportions of prosumers vs. σ; (d) optimal price vs. σ. Note. The solid and the dashed lines represent γ_c^* and γ_d^*, respectively. We use $\sigma = 1$ for Panel (a) and $I = 1$ for Panel (b). Please refer to Section EC.3 for the discussion for the parameter values. The common parameters are $d = 10$, $\mu = 4$, $c_0 = 1$, $c = 1$, $C = 2$, $I_0 = 4.5$, $\alpha = 1.2$, and $\beta = 0.95$. The patterns are robust to a wide range of parameter settings.

budget neutral. For more solar panel adoption, the policymaker imposes a tax on the consumers ($\theta < 0$) but provides subsidies to prosumers to lower the installation cost ($I_d < 0$). We note that the equilibrium is still stable with the intervention because each individual compares associated costs and benefits and makes a rational decision, as discussed after Lemma 2.

Even under the above intervention, some consumers find it optimal not to adopt solar panels after evaluating the associated costs and benefits. Although they make economically rational decisions, this does not necessarily imply that they are "satisfied" with the policy, which may cause challenges in implementation. We examine this issue from both absolute and relative perspectives.

From an absolute perspective, satisfaction may be associated with an improvement in individual welfare. Each prosumer provides environmental benefits that improve social welfare by α. Because these benefits are shared by all, prosumers may enhance regular consumer welfare. On the other hand, more prosumers increase the electricity price, negatively affecting consumer welfare. Therefore, the net impact of prosumers on consumer welfare depends on the relative magnitude of the environmental benefit α compared to the adverse effect of higher prices. A more detailed analysis is provided in the Appendix EC.2.

From a relative perspective, individuals may compare their welfare to others. In our context, consumers may perceive the intervention as more unfavorable if their welfare decreases more than that of prosumers. The above intervention may hurt consumers more than prosumers. Recall that a consumer with a larger roof has more incentives to be a prosumer. Such a consumer may become a prosumer even without any intervention. Proportional incentives disproportionately benefit these consumers, further reducing their energy costs and potentially widening the welfare gap between prosumers and consumers. Consequently, the proportional intervention may exacerbate unfairness while promoting prosumers.

To evaluate unfairness from an intervention and explore an alternative, we examine the difference in the cost per electricity usage (unit cost) between the two consumer groups before and after an intervention. This comparison of using the cost is equivalent to using welfare because environmental benefits are equally shared regardless of solar panel adoption. Although the unit cost of a regular consumer is equal to the electricity price regardless of the roof size, that of a prosumer decreases with the roof size because there is a fixed cost for every prosumer. In particular, we consider the unit electricity cost of the largest roof size. As we investigate the difference in differences and the intervention is linear with the roof size, our result would remain the same with a prosumer of a different roof size.

Specifically, we define $F_i(\gamma)$ as the unit cost of a consumer group i for a prosumer proportion γ, where $i = 1$ for a prosumer and $i = 2$ for a regular consumer. Suppose that there is no intervention and the prosumer proportion via self-selection is γ_d^*. Then, the unit cost of a prosumer with the largest roof ($s = 1$) is $F_{1b}(\gamma_d^*) = \frac{(d-\mu)sp(\gamma_d^*)+Is+I_0}{ds} = \frac{(d-\mu)p(\gamma_d^*)+I+I_0}{d}$. The unit cost of a consumer is just the utility price, that is, $F_{2b}(\gamma_d^*) = p(\gamma_d^*)$. The difference between two groups before an intervention is $\Delta_b(\gamma_d^*) = F_{1b}(\gamma_d^*) - F_{2b}(\gamma_d^*)$. Now consider that the policymaker adopts the intervention (I_d, θ). The unit costs become $F_{1a}(\gamma_c^*) = \frac{(d-\mu)p(\gamma_c^*)+(I+I_d)+I_0}{d}$ for the prosumer and $F_{2a}(\gamma_c^*) = p(\gamma_c^*) - \theta$ for the regular consumer. The difference after the intervention is $\Delta_a(\gamma_c^*) = F_{1a}(\gamma_c^*) - F_{2a}(\gamma_c^*)$. The next proposition shows the impact of the intervention on fairness.

Proposition 4. *Suppose that the policymaker implements the budget-neutral intervention (I_d, θ). If $\gamma_d^* < \gamma_c^*$, the intervention increases the unfairness between a regular consumer and the prosumer with the largest roof size, that is, $|\Delta_b(\gamma_d^*)| < |\Delta_a(\gamma_c^*)|$. Otherwise, the intervention decreases the unfairness.*

The above result shows that when the policymaker would like to improve solar panel adoption, the intervention achieves the socially optimal level of prosumers at the expense of fairness. Recall that a consumer with a larger roof size has stronger incentives to adopt solar panels. When subsidies are allocated proportionally to roof size, these consumers receive larger benefits, further lowering their average energy costs. At the same time, higher prosumer adoption raises the electricity price, thereby increasing the average cost for regular consumers. Consequently, the intervention exacerbates unfairness, as measured by the difference in average energy costs between prosumers and nonprosumers ($|\Delta_b(\gamma_d^*)| < |\Delta_a(\gamma_c^*)|$).

A natural question arises: Can the policymaker simultaneously improve the prosumer level and mitigate the unfairness? We propose an alternative intervention in which the solar panel subsidy decreases rather than increases with the roof size, denoted by $(I_{d,1-s}, \theta_{1-s})$. Like the current intervention, consumers face a charge or receive a subsidy proportional to their roof size with rate θ_{1-s}, resulting in an amount of $\theta_{1-s} \cdot s$. In contrast, the prosumer's rate $I_{d,1-s}$ applies in reverse proportion to the roof size. Under this intervention, a consumer with the roof size s who becomes a prosumer saves $p(\gamma) \cdot \mu \cdot s$ on average but needs to incur the solar panel installation cost $I \cdot s + I_{d,1-s} \cdot (1 - s) + I_0$. Thus, her net saving is $(p(\gamma)\mu - I - \theta_{1-s}d)s - I_{d,1-s} \cdot (1 - s) - I_0$. With this structure, we characterize $(I_{d,1-s}, \theta_{1-s})$ in the next proposition.

Proposition 5. *Suppose that $0 < \gamma_d^* < \gamma_c^*$. Define $I_{d,1-s} = \frac{1-\gamma_c^*}{\gamma_c^*}[(1 - \gamma_c^*)\mu p(\gamma_c^*) - (1 - \gamma_c^*)I - I_0]$ and $\theta_{1-s} = \frac{(\gamma_c^*)^2}{(1-\gamma_c^*)^2}\frac{I_{d,1-s}}{d}$. Compared to (I_d, θ), the intervention $(I_{d,1-s}, \theta_{1-s})$* (i) *achieves the socially preferred proportion of prosumers via self-selection ($\gamma_{d,1-s}^* = \gamma_c^*$) and* (ii) *reduces the unfairness ($|\Delta_{a,1-s}(\gamma_c^*)| < |\Delta_a(\gamma_c^*)|$).* (iii) *Moreover, its size is smaller ($|\theta_{1-s}| < |\theta|$).*

The alternative intervention $(I_{d,1-s}, \theta_{1-s})$ also has a relatively simple form and results in the same number of prosumers to (I_d, θ) (Proposition 5(i)). As it provides smaller subsidies to those who are well motivated (i.e., large s), it indeed reduces the unfairness regarding the unit electricity cost between consumers and prosumers (Proposition 5(ii)). Perhaps the most appealing feature of this intervention is that its magnitude is smaller than the previous one. In other words, Proposition 5(iii) suggests that the policymaker can achieve the same outcome by levying a smaller amount on regular consumers and, as such, providing a smaller subsidy to prosumers. It also means that the total amount of subsidies for prosumers is smaller. We note that this result, as to a decreasing investment subsidy schedule (e.g., tax credit), is aligned with Singh and Scheller-Wolf (2022), where a higher-tier customer group pays a higher fixed fee in FIT. However, both interventions are not equivalent in practice (Babich et al., 2020) and, hence, we complement the literature on social fairness with prosumers. This result also produces actionable insights for policymakers. If policymakers adopt a uniform tax credit ratio (e.g., 30%) for more prosumers regardless of their installation cost, it will exacerbate social unfairness. Instead, they should consider providing more subsidies to those with relatively small roof sizes rather than large ones. By doing so, they can have more prosumers and also mitigate the unfairness between different groups of consumers.

A salient feature of our model is to incorporate the demand intermittency (σ) from the prosumers' generation. Then, how do the current and the proposed interventions perform with respect to such intermittency? Figure 3 illustrates the comparison between them, where the solid line represents the current intervention and the dot-dashed line represents the proposed one. In both panels, we observe that the solid line is above the dot-dashed line, and the gap between them diminishes in σ. Figure 3(a) demonstrates that as demand intermittency increases, the proposed intervention leads to less unfairness than the current, but the unfairness reduction decreases. Similarly, Figure 3(b) shows that the proposed intervention can save budget to achieve the same prosumer level, but the saving decreases as demand intermittency increases. Such diminishing benefits are because the socially optimal prosumer

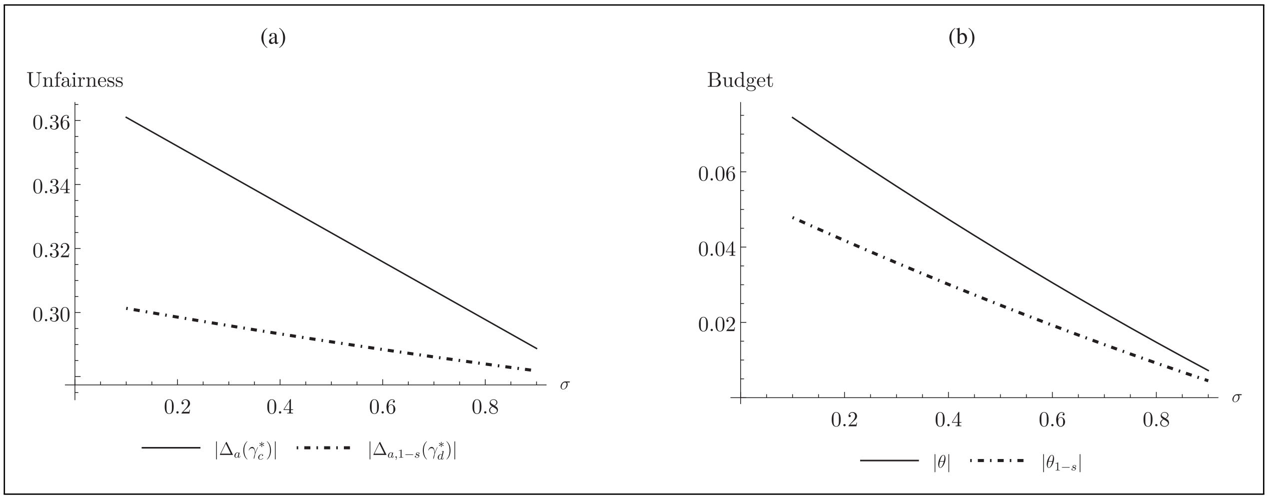

Figure 3. The comparisons of the current and the proposed interventions. (a) Unfairness reduction; (b) budget reduction. Note. The solid and the dot-dashed lines represent the current and the proposed intervention, respectively. The common parameters are $d = 10$, $\mu = 4$, $c_0 = 1$, $c = 1$, $C = 2$, $l = 1$, $l_0 = 4.5$, $\alpha = 1.2$, and $\beta = 0.95$.

level and the self-selected level become closer. Yet, both panels show that the proposed intervention achieves the same prosumer level with more unfair reduction but less budget.

5 Extensions

To gain sharp insights, we adopt some stylized features in the base model. In this section, we extend our base model in five different directions. First, we explore the case where prosumers can sell surplus power back to the grid through net metering. Second, we examine an alternative pricing mechanism. Third, we introduce green consumers who derive non-financial utility from solar panels. Fourth, we compare the fairness across groups rather than individuals. Finally, we modify the demand structure, making it independent of roof size.

5.1 Net Metering: Prosumers Selling Back to the Grid

In the base model, we focus on the scenario that prosumers' renewable energy generation is not sufficient to cover their demand ($\mu + \sigma < d$). However, with the advancement in solar technology or favorable environmental conditions, it is possible that a large proportion of prosumers may have extra solar energy ($d < \mu + \sigma$) and can sell surplus electricity back to the grid. In this subsection, we relax the assumption of $\mu + \sigma < d$ and investigate the case where prosumers can generate more solar energy than needed. This practice is referred to by different names in practice. If the prosumers receive credits worth the retail price, it is often called net metering. If they receive credits as much as the wholesale price, it is called net billing. As the main mechanism, selling extra energy to the grid, is common, we do not distinguish these terms. Instead, we generalize the scenario when the prosumer can sell extra solar energy to the grid by introducing the net metering rate b, which is similar to Hu et al. (2015). That is, a prosumer can sell their surplus electricity at a rate of b back to the grid. Letting the electricity price, in this case, be p_b, the utility firm has the following revenue and expenditure:

$$
\begin{aligned}
&p_b \int_0^{1-\gamma} (d \cdot s)\, ds + p_b E\left[\int_{1-\gamma}^{1} (d-\xi)^+ \cdot s ds\right] \\
&\quad = c_0 \cdot Q^*(\gamma) + c \cdot E\left[\min\left\{Q^*(\gamma), D_u\right\}\right] \\
&\qquad + C \cdot E\left[\left(D_u - Q^*(\gamma)\right)^+\right] + b \cdot E\left[\int_{1-\gamma}^{1} (\xi - d)^+ \cdot s ds\right].
\end{aligned} \tag{7}
$$

The two terms on the left-hand side represent the revenue from normal consumers and prosumers, respectively. On the right-hand side, the first term is the internal capacity cost. The second and third terms are the supply costs from internal and external sources, and the last term is the cost of purchasing unconsumed solar energy from prosumers.

Following the similar analysis in Section 4.1, we can derive the electricity price and summarize its properties in the following proposition.

PROPOSITION 6. *Suppose that the prosumers can sell extra solar energy at the rate of $b \geq 0$ to the grid. Define* $A = 4\sigma c_0[d - (2\gamma - \gamma^2)(\mu + \sigma - 2\sigma\beta)] + 4\sigma C(2\gamma - \gamma^2)\sigma(1-\beta)^2 +$

$b(2\gamma-\gamma^2)(\mu+\sigma-d)^2$. Then, the electricity price is

$$p_b = \begin{cases} \frac{A+4\sigma c[d-(2\gamma-\gamma^2)(\mu+\sigma-2\sigma\beta)-(2\gamma-\gamma^2)\sigma\beta^2]}{4\sigma(1-\gamma)^2 d+(2\gamma-\gamma^2)(d-\mu+\sigma)^2} \\ \qquad \textit{if } (2\gamma-\gamma^2)(\mu+\sigma) < d < \mu+\sigma, \\ \frac{A+\left[d\left(\frac{d}{2\gamma-\gamma^2}-2\mu+2\sigma\right)+(2\gamma-\gamma^2)(\mu+\sigma-2\sigma\beta)(\mu-3\sigma+2\sigma\beta)\right]}{4\sigma(1-\gamma)^2 d+(2\gamma-\gamma^2)(d-\mu+\sigma)^2} \\ \qquad \textit{if } d < (2\gamma-\gamma^2)(\mu+\sigma). \end{cases}$$

Despite the closed-form expression, examining the price's sensitivity in general is challenging. Nonetheless, we derive properties for p_b for some special cases.

COROLLARY 1. *If $c = 0$, the price increases in the proportion of prosumers (γ) if and only if $b > b_\gamma$, increases in the volatility (σ) if and only if $b > b_\sigma$ and the efficiency (μ) if and only if $b > b_\mu$ of renewable energy generation, where b_γ, b_μ, and b_σ are defined in (EC.45), (EC.46), and (EC.47) in the Online Appendix, respectively.*

The result shows that even if more solar energy from prosumers (i.e., a larger γ and/or a larger μ) can be sent back to the grid and serve the regular consumers, the electricity price will still increase as long as the net metering rate is high enough. The intuition of this result is as follows: If b is relatively low, the utility company can get extra solar energy almost for free, then with more extra solar energy (a larger γ and/or a larger μ), the electricity price will drop; if b is relatively high, the utility firm needs to acquire the extra solar energy at a high cost, then with more extra solar energy (a larger γ and/or a larger μ), the electricity price will become higher. We formalize this rationale in the next corollary.

COROLLARY 2. *If $c = 0$ and $b = p_b$, the price has the same expression as that under the base model (i.e., Proposition 1 with $c = 0$). Thus, the price increases in the proportion of prosumers (γ), the volatility (σ), and the efficiency (μ) of renewable energy generation.*

In practice, the net metering rate can sometimes be as high as the retail rate of the electricity price in some regions, such as Florida (Florida Power & Light, 2025). The above corollary illustrates that if the net metering rate coincides with the electricity price, then the results from the base model will carry over.

Then, how are the net metering rate, the optimal prosumer level, and unfairness related? Especially we are interested in comparing net metering practices to our proposed intervention regarding unfairness. To have more prosumers, policymakers may set a high net metering rate. However, its effectiveness is likely to be much more limited than our proposed intervention. The benefits of net metering accrue only to those prosumers who generate surplus energy, which predominantly occurs under favorable environmental conditions for solar energy. This also implies that if environmental conditions are less favorable to solar energy generation, the impact of net metering is significantly limited, even with a high net metering rate.

Net metering also involves an inherent trade-off. On the one hand, a high rate would motivate more consumers to be prosumers. As Figure 4(a) illustrates, a proper net metering rate b can equate the self-selected prosumer level to the socially optimal prosumer level. That is, there exists b such that $\gamma_d^*(b) = \gamma_c^*(b)$. On the other hand, a high net metering rate would exacerbate social disparity regarding the electricity price as prosumers' actual cost will be even lower, as shown in Figure 4(b). The unfairness level is increasing in the net metering rate. Thus, achieving the socially optimal prosumer level through a high net metering rate comes at the expense of increased social disparity.

One possible win-win case would be when (1) the prosumer's extra energy generation after satisfying their demand is substantially large, and (2) the regular consumers use the extra prosumer-generated energy at a very low rate. We note that a high net metering rate is a likely necessary condition for the first condition, but a low net metering rate is one for the second condition. Thus, for the win–win case to arise, most prosumers should adopt solar panels for environmental reasons despite little to no cost savings at a low net metering rate. As the financial aspects of solar panels are still important for typical consumers (Cohen, 2023; Ogletree, 2024), we believe that the mitigating effect of net metering on social disparity is somewhat limited.

In contrast to the limitations of net metering practices, our proposed intervention provides more comprehensive incentives. It is particularly advantageous for prosumers who derive minimal or no benefits under existing systems. Moreover, our intervention ensures that all prosumers benefit consistently, regardless of fluctuations in day-to-day operations, thereby addressing the shortcomings of net metering and offering a more equitable and effective approach.

5.2 *Ex-Post Electricity Price*

In the base model, we assume that the utility firm sets the price with a unit profit margin of m in expectation. Although this is often the case, this committed pricing mechanism does not guarantee a margin, and the firm may incur a loss ex-post, potentially endangering the firm's survival. To ensure continuity of electricity supply, the electricity price can be set ex-post, which we consider in this extension. Nevertheless, when consumers decide whether to be prosumers, the price has not been set yet. Therefore, the consumers should take the expected ex-post electricity price into consideration, which is expressed as

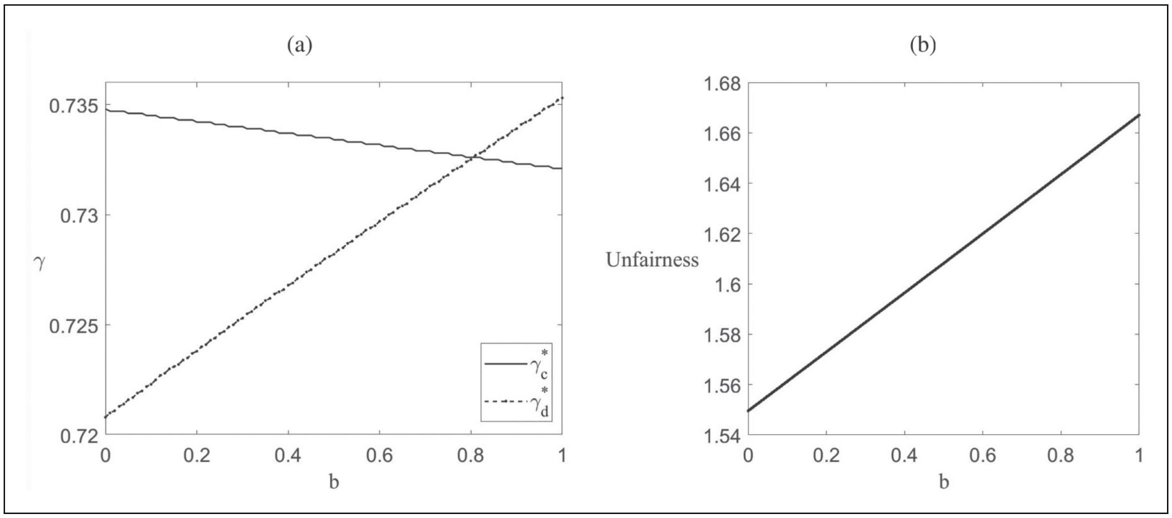

Figure 4. Optimal prosumer levels and unfairness under net metering. (a) Optimal prosumer levels; (b) unfairness.

follows:

$$p_2(Q^*(\gamma),\gamma) = E\left[\frac{c_0 \cdot Q^*(\gamma) + c \cdot \min\{Q^*(\gamma), D_u(\gamma)\} + C \cdot (D_u(\gamma) - Q^*(\gamma))^+}{D_u(\gamma)}\right]. \quad (8)$$

The next lemma provides the closed-form expression of the expected ex-post price.

LEMMA 3. *For a given γ, the expected ex-post price is*

$$p_2(\gamma) = \left(\frac{CV_u}{2\sqrt{3}} + \frac{2\beta - 1}{2}\right)\left(c_0 \ln \frac{CV_u + \sqrt{3}}{CV_u - \sqrt{3}} - (C - c) \ln \frac{CV_u + \sqrt{3}}{CV_u + (2\beta - 1)\sqrt{3}}\right) + c\beta + C(1 - \beta),$$

where $CV_u = \frac{\sigma_{D_u}}{E[D_u]}$.

With the result in Lemma 3, we can characterize how prosumers' proportion, their generation efficiency, and volatility affect the expected price in the following proposition.

PROPOSITION 7. *The expected ex-post electricity price increases in the proportion of prosumers (γ), the volatility (σ), and the efficiency (μ) of renewable energy generation.*

Although the price expression becomes more complicated in this case, Proposition 7 shows that the main result from the base model (Proposition 1) remains unchanged with this alternative setting. The main intuition of this result is consistent with the base model that the prosumers' electricity generation inherently has more variability and burdens the utility firm's operations.

Then, how is the ex-post price different from the ex-ante price? As $p_2(\gamma)$ imposes substantial analytical challenges, we compare both prices numerically in Figure 5. Panel (a) in the figure shows the percentage difference between p and p_2, that is, $\frac{p_2 - p}{p_2} \times 100$. While the difference increases in σ, the difference is positive but much less than 1%. It suggests that the ex-ante price is lower than the ex-post price, but serves as a good approximation of the ex-post price. Furthermore, our results under the ex-ante price will hold under the ex-post pricing. For example, Panel (b) shows the percentage difference of the effectiveness of the proposed intervention compared to the current one between p and p_2, that is, $\frac{(\Delta_a(\gamma_c^*|p_2) - \Delta_{a,1-s}(\gamma_c^*|p_2)) - (\Delta_a(\gamma_c^*|p) - \Delta_{a,1-s}(\gamma_c^*|p))}{(\Delta_a(\gamma_c^*|p_2) - \Delta_{a,1-s}(\gamma_c^*|p_2))} \times 100$. It also shows the intervention effectiveness under both pricing mechanisms is quite close.

5.3 Green Consumers

We have assumed that consumers consider only the financial aspects of solar panel adoption. However, some consumers may become prosumers because they appreciate green energy despite the financial loss. In this subsection, we discuss the case when there are some consumers who enjoy such intangible benefits. Specifically, we define green consumers as those who obtain additional utility e per solar panel. We assume that green consumers are independent of their residential conditions, such as roof size. Therefore, the roof sizes of both green and regular consumers are uniformly distributed equally in $[0, 1]$. For ease of exposition, let G and R denote green and regular consumers, respectively. Without loss of generality, we model that $\phi \in [0, 1]$ of the whole consumers are G and the remaining $1 - \phi$ are R. Then, if we let γ_G and γ_R as the proportion of prosumers in G and R, respectively, the total proportion of prosumers is $\gamma_{d,T}(\phi) = \phi\gamma_G + (1 - \phi)\gamma_R$. For a green consumer with roof size s, the difference of her

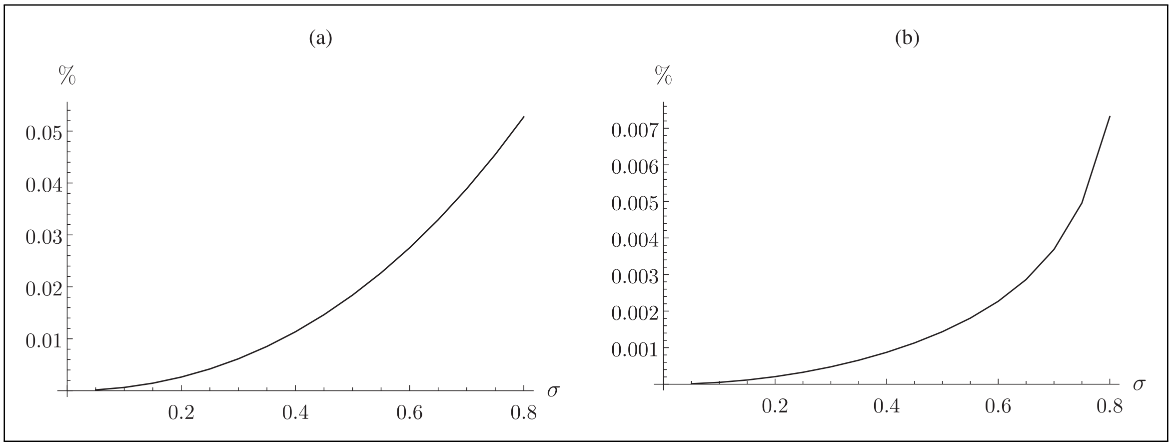

Figure 5. Comparisons of ex-ante and ex-post prices and intervention effectiveness. (a) Price comparison in σ; (b) intervention effectiveness in σ. Note. Panel (a) shows the percentage difference between p and p_2, that is, $\frac{p_2-p}{p_2}\times 100$. Panel (b) shows the percentage difference in the mitigated unfairness between the current and the proposed interventions, that is, $\frac{(\Delta_a(\gamma_c^*|p_2)-\Delta_{a,1-s}(\gamma_c^*|p_2))-(\Delta_a(\gamma_c^*|p)-\Delta_{a,1-s}(\gamma_c^*|p))}{(\Delta_a(\gamma_c^*|p_2)-\Delta_{a,1-s}(\gamma_c^*|p_2))}\times 100$. The common parameters are $d=10$, $\mu=2$, $\sigma=1$, $c_0=2$, $c=0.5$, $C=1.5$, $I=1$, $I_0=3$, $\alpha=1.8$, and $\beta=0.95$.

expected utility between prosumer and consumer is $g_G(s,\gamma)=(p(\gamma)\mu-I+e)s-I_0$, where γ means there are γ proportion of prosumers.

LEMMA 4. *There exist unique γ_R^* and γ_G^* that solve $g(1-\gamma_R,\gamma_{d,T})=0$ and $g_G(1-\gamma_G,\gamma_{d,T})=0$, respectively. In addition, $\gamma_R^*<\gamma_G^*$ and both γ_R and γ_G increases in ϕ.*

Because the total proportion of prosumers is defined as $\gamma_{d,T}^*=\phi\gamma_G^*+(1-\phi)\gamma_R^*$, more prosumers in G than R in Lemma 4 implies that the existence of G leads to more prosumers in total. Therefore, the most results in the base model will be magnified as ϕ increases. For example, $\gamma_{d,T}^*$ increases in ϕ.

It is worthwhile to discuss the impact of green consumers on unfairness. In Section 4.3, we compare the average unit costs of regular consumers and prosumers with the largest roof. As there are two types of prosumers, we examine unfairness in G and R, respectively. When we use a prosumer with the largest roof as a reference point, unfairness in G and R will be the same. This is because the roof sizes of both types of prosumers are identical, incurring the same amount of cost. However, if we use a prosumer with a different quantile (e.g., the mean roof size) within the group, the comparison result may change. To examine this clearly, recall that the unit cost of a prosumer with roof size s is $\frac{(d-\mu)p(\gamma)+I}{d}+\frac{I_0}{d\cdot s}$. Because all the nonprosumers' cost is p, the unit cost difference is $\frac{1}{d}\left(-\mu p(\gamma)+I+\frac{I_0}{s}\right)<0$, which is decreasing in s. It implies that the unfairness level measured by the unit cost difference is higher when s is higher. For two prosumers at the same quantile within each group, $\gamma_G^*>\gamma_R^*$ implies that the roof size of a prosumer in R is larger than in G. That is, unfairness in R is greater than in G. We summarize this finding in the next corollary.

COROLLARY 3. *The unfairness between prosumers and consumers in G is smaller than in R.*

5.4 Egalitarian Fairness

In the base model, we have shown that more prosumers will make an individual regular consumer worse off by resulting in a higher electricity price and proposed a measure of unfairness at a representative individual level. Another approach to measure fairness is to compare the total utilities between groups. The max-min (egalitarian) fairness (e.g., Bertsimas et al., 2011) is a common and well-studied notion of fairness, where fairness is achieved by maximizing the minimum utility levels of all the participants. Since the objective is a cost in our context, this is equivalent to the min-max fairness. We compare this new socially fair proportion of prosumers to the other two (the self-selection equilibrium and total-social-cost-minimizing) proportions.

We define $F_1^a(\gamma)$ and $F_2^a(\gamma)$ as the aggregated cost of prosumers and regular consumers, respectively. Then, the aggregated cost of prosumers can be written as

$$\begin{aligned}F_1^a(\gamma)&=p(\gamma)E\int_{1-\gamma}^{1}(s\cdot d-s\cdot\xi)ds+\int_{1-\gamma}^{1}(s\cdot I+I_0)ds\\&=\frac{1}{2}(d-\mu)p(\gamma)[1-(1-\gamma)^2]+\frac{1}{2}I[1-(1-\gamma)^2]+I_0\gamma\end{aligned}\tag{9}$$

and the aggregated cost of the regular consumer group can be expressed as

$$F_2^a(\gamma)=p(\gamma)\int_0^{1-\gamma}(s\cdot d)ds=\frac{1}{2}d(1-\gamma)^2p(\gamma).\tag{10}$$

In the min-max fairness, we seek to identify an optimal value of γ, minimizing the maximum cost of the two groups. This is equivalent to the policymaker solves the following problem:

$$\min_{\gamma} \max\{F_1(\gamma), F_2(\gamma)\}. \tag{11}$$

The next lemma characterizes the optimal proportion of prosumers for the min-max fairness.

LEMMA 5. *Suppose* $[C(1-\beta)^2 - c(1-2\beta)]\sigma \leq \left(c + \frac{I}{2d-\mu}\right)\mu$. *There exists a* γ_0 *such that* $F_1^a(\gamma_0) - F_2^a(\gamma_0) = 0$. *Moreover,* $F_1^a(\gamma) - F_2^a(\gamma) < 0$ *if and only if* $0 \leq \gamma < \gamma_0$.

The above result indicates that when it is too costly to satisfy all consumers' demands using only internal nonrenewable sources (cd), having prosumers is beneficial for fairness. If there are too few ($\gamma < \gamma_0$) prosumers, the aggregate cost of prosumers is smaller ($F_1(\gamma) < F_2(\gamma)$) than that of regular consumers. If there are too many prosumers, the opposite is the case. Thus, to minimize the maximum aggregate cost of the two groups, the cost of both groups should be balanced with some intermediate number of prosumers ($F_1(\gamma_0) = F_2(\gamma_0)$). Then, how does this fair proportion of prosumers differ from the others, namely γ_c^* and γ_d^*?

PROPOSITION 8. (i) *The fair proportion of prosumers (γ_0) is decreasing in the installation cost (I or I_0) and increasing in the renewable energy generation efficiency (μ).* (ii) *The fair proportion of prosumers is increasing in the renewable energy generation intermittency (σ).*

Proposition 8(i) shows that the fair proportion behaves like socially optimal and self-interested equilibrium proportions when the renewable energy generation efficiency (μ) and affordability (I or I_0) improve. Interestingly, Proposition 8(ii) suggests that a socially optimal level of prosumer can exhibit a different pattern depending on its objective. Although the optimal proportion minimizing the total cost (γ_c^*) decreases in the prosumers' generation intermittency (Proposition 2(iii)), the fair proportion minimizing the unfairness level (γ_0) indeed increases in the intermittency like the equilibrium proportion by self-selection (γ_d^*). This result implies that policymakers should implement the policy after carefully considering their objectives, as a naive *socially-good* objective may require a quite different policy.

5.5 Independent Demand of Roof Size

In the base model, we assume that a consumer's demand is correlated with her roof size. However, various factors affect the demand. To examine the robustness of our results, we adopt two alternative demand functions and analyzed the models accordingly.

First, suppose that the demand is independent of the roof size and still deterministic. Specifically, we assume that all consumers have the same demand, which is common when studying policies in conjunction with intermittency in literature (e.g., Kaps et al., 2023; Kök et al., 2015). Under this assumption, the aggregated demand for the utility firm becomes

$$D_u(\gamma) = \int_0^{1-\gamma} d ds + \int_{1-\gamma}^{1} (d - \xi \cdot s) ds = d - \frac{1}{2}\xi(2\gamma - \gamma^2). \tag{12}$$

We note that (12) is obtained by replacing $\frac{1}{2}d$ in (3) with d. As all the results are based on D_u, our main results can be modified to incorporate the same demand assumption by substituting d into $\frac{1}{2}d$.

Next, we examine the scenario where demand is not only independent of the roof size but also random. Specifically, we investigate the case where the aggregated demand D is uniformly distributed between $d - \sigma_d$ and $d + \sigma_d$. Note that a prosumer still relies on the utility firm. That is, her minimum demand is greater than the maximum generation for tractability, that is, $d - \sigma_d > \mu + \sigma$.

To analyze this case, we first define the utility firm's net demand, solve for the optimal capacity for that demand, and investigate how the electricity price changes, eventually affecting the optimal prosumer levels and effectiveness of the intervention. Similar to the base model, the net demand for the utility firm is expressed as

$$D_u(\gamma) = D - \int_{1-\gamma}^{1} \xi s \, ds = D - \frac{1}{2}\xi(2\gamma - \gamma^2), \tag{13}$$

where D is a random variable. As there are two random variables D and ξ instead of one, we analyze the following expression even after assuming independence between D and ξ.

$$P(D_u(\gamma) < Q) = P\left(D - \frac{1}{2}\xi(2\gamma - \gamma^2) < Q\right)$$
$$= \int_{d-\sigma_d}^{d+\sigma_d} \int_{\max\left\{\mu-\sigma, \frac{2(x-Q)}{2\gamma-\gamma^2}\right\}}^{\mu+\sigma} \frac{1}{2\sigma}\frac{1}{2\sigma_d} \, d\xi dx = \beta.$$

Because the range of integration itself depends on Q, there are multiple cases to analyze even with the uniform distribution assumption for f and g, which significantly complicates the analysis. The next lemma characterizes the optimal quantity.

LEMMA 6. *Assume* $D \sim U[d - \sigma_d, d + \sigma_d]$ *and* $d - \sigma_d > \mu + \sigma$. *The internal generation capacity is characterized in (EC.176).*

The complex form of $Q(\gamma)$ hinders us from analytically deriving the closed form of optimal γ. To examine whether our main results hold with random supply and demand, we conduct extensive numerical analysis and illustrate a representative case in Figure 6. Figure 6(a) illustrates the result consistent with our main findings that the price increases in the prosumer proportion (γ). Also, Figure 6(b) shows that policymakers may want to incentivize consumers for low σ.

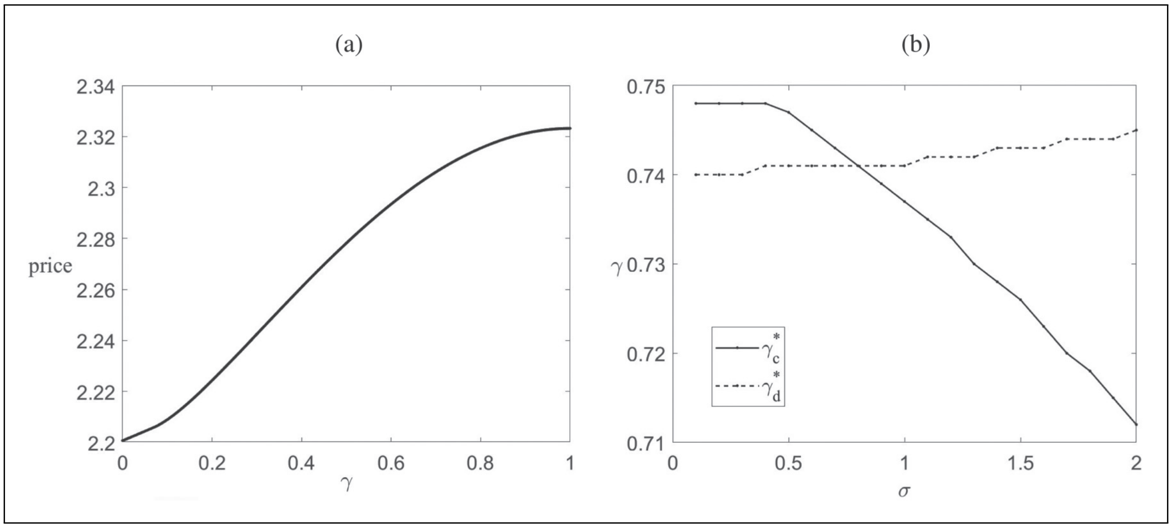

Figure 6. Results under random demand and supply. (a) Price vs. γ; (b) optimal prosumer proportions. Note. The common parameters used are $\beta = 0.95$, $d = 10$, $\sigma_d = 2$, $\mu = 4$, $\sigma = 2$, $c = 1$, $c_0 = 1$, $C = 2$, $\alpha_1.2$, $l = 0.5$, and $l_0 = 2.2$.

6 Conclusion

The growing affordability and efficiency of renewable energy technologies enable traditional consumers to transition from passive users to active participants, known as prosumers. Prosumers harness renewable energy sources on their properties, contributing significantly to greenhouse gas emission reduction and reducing dependence on fossil fuels. However, most prosumers connect to the electricity grid as a backup when their renewable energy generation falls short. Consequently, utility companies must reserve capacity for prosumers, incurring costs that remaining traditional consumers ultimately shoulder.

As the prosumer population grows, these costs escalate rapidly, burdening remaining consumers, even without counting the fixed costs of maintaining the electrical grid. In this paper, we study the ramifications of an increasing prosumer population on traditional consumers.

Our study introduces a stylized model to examine the impact of prosumers on different consumer groups and society as a whole, taking into account the efficiency and volatility of solar panel energy generation. Our analysis indicates that although prosumers may help reduce nonrenewable energy generation and the utility firm save related costs, they also negatively affect the rest of society. The inherent intermittency in prosumers' solar panel generation imposes more uncertainty on the existing grid, increasing the electricity price and subsequently raising the regular consumers' energy bill. Notably, this insight stands even without factoring in the utility firm's fixed costs. This distinction is crucial, as it highlights the need for policymakers to consider factors other than fixed costs when designing interventions.

We also derive the optimal proportion of prosumers for various objectives. In particular, we compare the equilibrium level, which is determined by consumers' self-selection, to the socially optimal level. Our findings highlight a divergence between the self-interested equilibrium and socially optimal levels, particularly in response to variations in prosumers' renewable energy generation intermittency. High intermittency leads to a decrease in the socially optimal proportion but an increase in self-selected prosumers. This is because prosumers, like regular consumers, depend on the grid during periods of significantly reduced energy generation due to intermittency. The utility firm must prepare for such scenarios with sufficient capacity, which, in turn, raises electricity prices. As prices increase, being a prosumer becomes more economically attractive, encouraging more individuals to be prosumers and subsequently increasing the social cost, which is against the socially optimal direction.

Motivated by the 2023 federal tax credit for solar panel installation costs in the United States, we analyze the impact of this subsidy relative to roof size. While the right level of intervention can optimize prosumer adoption, it may exacerbate social inequality by disproportionately benefiting those who already have strong incentives to become prosumers. In response, we propose a reverse-linear subsidization approach to reduce social inequality. Our results also indicate that this proposed subsidization requires less funding to achieve the same prosumer adoption rates. In conclusion, our research illuminates prosumers' negative externalities on society and offers actionable insights for policymakers and utility companies to consider in their decision-making.

We briefly point out a few limitations and provide some directions for future research. Based on the current study, many directions are worth further exploration. First, the energy storage system is poised to be a valuable resource for future power grids due to technological advancements. The battery storage system allows prosumers to store the excess solar power for future use. It will improve the self-consumption of solar energy and consequently affect the price of electricity. Future research can examine the impact of battery storage systems on the energy market. Second, we assume that the consumer roof size follows a uniform distribution and deterministic demand for analytical tractability. This assumption allows us to capture the heterogeneity of consumers parsimoniously. However, it could be valuable to relax this assumption and explore the impact of a more generalized distribution of consumer heterogeneity in future research. Third, we focus on markets with a single electricity supplier for the consumers for ease of analysis. However, some other markets are deregulated and allow competition among the suppliers. It is well-known that competition tends to result in lower prices. Future research can extend the model to explore the interplay between prosumers and deregulation. Finally, to study the impact of prosumers from a strategic perspective, we abstract away the fluctuations of solar power during the day. Instead of investigating solar power variability from an aggregate level, future research can focus on the operational level by explicitly considering solar fluctuations during the day. Notwithstanding these limitations, the current study presents a critical step in better understanding the unintended consequences of the emergence of the prosumers and provides mitigation strategies against the (unintended) unfairness between different consumer groups.

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ORCID iDs

Junghee Lee https://orcid.org/0000-0001-9527-9777
Lai Wei https://orcid.org/0000-0003-2083-1752
Ming Hu https://orcid.org/0000-0003-0900-7631
Yinliang (Ricky) Tan https://orcid.org/0000-0001-8971-818X

Supplemental Material

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Notes

1. The consumer heterogeneity parameter s could be interpreted more broadly. Consumer-specific factors that affect both cost and generation can play the same role (e.g., Gautier et al., 2018), maintaining the resulting fairness implications. We refer to the heterogeneity as roof size because it is one of the primary factors determining installation cost and generation capacity.
2. U.S. Energy Information Administration publicizes various energy-related information on its website, www.eia.gov. According to Table 2.2, Sales and Direct Use of Electricity to Ultimate Customers, the electricity sales to the residential sector were 1,509,233 thousand megawatthours in 2022. Table 1.2.E, Net Generation by Energy Source: Residential Sector, 2015-February 2025, shows that the estimated net generation by solar panels from the residential sector was 39,510 thousand megawatthours in 2022, which is about 2.6% of the electricity sales to the residential sector.
3. We note that the linearity of (5) is a result of the uniform distribution assumption.
4. Even if $(c + c_0)\mu \leq I + I_0$, there still exists a unique stable equilibrium. However, it may be zero prosumers depending on the relative magnitude of I and I_0. The detailed conditions for the equilibrium are provided in the proof of Lemma 2.
5. If adoption happens to exceed γ_d^*, consumers with smaller roofs than γ_d^* face higher unit costs and would prefer to revert to regular consumption, assuming reversibility. This adjustment drives the system back toward the stable equilibrium γ_d^*.
6. We note that the proposed mechanism is the solution to an optimization problem with the constraint of the neutral budget. Hence, our solution approach can be extended to an unconstrained optimization problem without a neutral budget. For example, the 2023 federal tax credit for solar panel installation costs in the United States is an immediate application of our approach.
7. In some contexts (e.g., when intermittency (σ) is high), a lower prosumer level may be socially optimal. In such cases, the proportional intervention imposes greater tax burdens on those with larger roof sizes, increasing their energy costs and thereby reducing unfairness.

References

Aflaki S and Netessine S (2017) Strategic investment in renewable energy sources: The effect of supply intermittency. *Manufacturing & Service Operations Management* 19(3): 489–507.

Agrawal V, Atasu A and Van Wassenhove LN (2019) OM Forum—New opportunities for operations management research in sustainability. *Manufacturing & Service Operations Management* 21(1): 1–12.

Agrawal V, Toktay B and Yücel S (2022) Non-ownership business models for solar energy. *Manufacturing & Service Operations Management* 24(4): 2048–2063.

Al-Gwaiz M, Chao X and Wu OQ (2017) Understanding how generation flexibility and renewable energy affect power market competition. *Manufacturing & Service Operations Management* 19(1): 114–131.

Alizamir S, de Véricourt F and Sun P (2016) Efficient feed-in-tariff policies for renewable energy technologies. *Operations Research* 64(1): 52–66.

Angelus A (2021) Distributed renewable power generation and implications for capacity investment and electricity prices. *Production and Operations Management* 30(12): 4614–4634.

Arora P, Wei W and Solak S (2021) Improving outcomes in child care subsidy voucher programs under regional asymmetries. *Production and Operations Management* 30(12): 4435–4454.

Babich V, Lobel R and Yücel S (2020) Promoting solar panel investments: Feed-in-tariff vs. tax-rebate policies. *Manufacturing & Service Operations Management* 22(6): 1148–1164.

Barrera A (2025) Mexico moves forward with energy reform to strengthen dominant roles of state companies. *Reuter*. Available at: https://tinyurl.com/tkj3awp9 (accessed 25 April 2025).

Bertsimas D, Farias VF and Trichakis N (2011) The price of fairness. *Operations Research* 59(1): 17–31.

Cai DW, Adlakha S, Low SH, et al. (2013) Impact of residential PV adoption on retail electricity rates. *Energy Policy* 62: 830–843.

Cohen MC, Lobel R and Perakis G (2016) The impact of demand uncertainty on consumer subsidies for green technology adoption. *Management Science* 62(5): 1235–1258.

Cohen SS (2023) Are solar panels worth it? A complete guide to help you decide. *Forbes*. Available at: https://tinyurl.com/mpp35dbd (accessed 7 September 2023).

Cordera F, Moreno R and Ordoñez F (2023) Unit commitment problem with energy storage under correlated renewables uncertainty. *Operations Research* 71(6): 1960–1977.

Costello KW and Hemphill RC (2014) Electric utilities' 'death spiral': Hyperbole or reality? *The Electricity Journal* 27(10): 7–26.

Department of Energy (2023) Homeowner's guide to the federal tax credit for solar photovoltaics. Available at: https://tinyurl.com/2uv5s8nf (accessed 25 April 2025).

Devlin T (2023) Federal solar tax credit explained. Available at: https://www.saveonenergy.com/solar-energy/solar-tax-credit (accessed 25 April 2025).

Environmental Protection Agency (2025) U.S. Electricity Grid & Markets. Available at: https://tinyurl.com/tvd4y8f3 (accessed 25 April 2025).

Florida Power & Light (2025) Frequently asked questions. Available at: https://www.fpl.com/clean-energy/net-metering/faq.html (accessed 25 April 2025).

Gautier A, Jacqmin J and Poudou JC (2018) The prosumers and the grid. *Journal of Regulatory Economics* 53: 100–126.

Girotra K and Netessine S (2013) OM Forum—Business model innovation for sustainability. *Manufacturing & Service Operations Management* 15(4): 537–544.

Guajardo J (2018) Third-party ownership business models and the operational performance of solar energy systems. *Manufacturing & Service Operations Management* 20(4): 788–800.

Hu S, Souza GC, Ferguson ME, et al. (2015) Capacity investment in renewable energy technology with supply intermittency: Data granularity matters! *Manufacturing & Service Operations Management* 17(4): 480–494.

Kampman B, Blommerde J and Afman M (2016) The potential of energy citizens in the european union. *CE Delft*. Available at: https://tinyurl.com/4b85xj9w (accessed 15 July 2019).

Kaps C, Marinesi S and Netessine S (2023) When should the off-grid sun shine at night? Optimum renewable generation and energy storage investments. *Management Science* 69(12): 7633–7650.

Kök AG and Shang K, Yücel (2015) Impact of electricity pricing policies on renewable energy investments and carbon emissions. *Management Science* 64(1): 131–148.

Krass D, Nedorezov T and Ovchinnikov A (2013) Environmental taxes and the choice of green technology. *Production and Operations Management* 22(5): 1035–1055.

Kuznetsova E and Anjos MF (2020) Challenges in energy policies for the economic integration of prosumers in electric energy systems: A critical survey with a focus on Ontario (Canada). *Energy Policy* 142: 111429.

Ma G, Lim MK, Mak HY, et al. (2019) Promoting clean technology adoption: To subsidize products or service infrastructure? *Service Science* 11(2): 75–95.

Mamaghani FF and Çakanyildirim M (2024) Harvesting solar power foments prices in a vicious cycle: Breaking the cycle with price mechanisms. *Operations Research* 72(4): 1505–1525.

Navia Simon D and Diaz Anadon L (2025) Power price stability and the insurance value of renewable technologies. *Nature Energy* 10(3): 329–341.

NPR (2020) Das green old deal. Available at: https://www.npr.org/transcripts/797322305 (accessed 25 April 2025).

Ogletree A (2024) How much do solar panels cost in 2024? *Forbes*. Available at: https://www.forbes.com/advisor/au/solar/solar-installation-cost/ (accessed 25 April 2025).

Ontario Energy Board (2025) Electricity rates. Available at: https://tinyurl.com/2bm78u73 (accessed 12 May 2025).

Ovchinnikov A, Pun H and Raz G (2023) The impact of inventory risk on market prices under competition. *Decision Sciences* 54(1): 29–42.

Parker G, Tan B and Kazan O (2019) Electric power industry: Operational and public policy challenges and opportunities. *Production and Operations Management* 28(11): 2738–2777.

Raz G and Ovchinnikov A (2015) Coordinating pricing and supply of public interest goods using government rebates and subsidies. *IEEE Transactions on Engineering Management* 62(1): 65–79.

Satchwell A, Mills A and Barbose G (2015) Quantifying the financial impacts of net-metered PV on utilities and ratepayers. *Energy Policy* 80: 133–144.

Singh SP and Scheller-Wolf A (2022) That's not fair: Tariff structures for electric utilities with rooftop solar. *Manufacturing & Service Operations Management* 24(1): 40–58.

Solar Eclipsed (2018) Rooftop solar remains marginal in America. *The Economist*. Available at: https://tinyurl.com/kwzfz6tb (accessed 15 July 2019).

Sunar N and Birge JR (2019) Strategic commitment to a production schedule with uncertain supply and demand: Renewable energy in day-ahead electricity markets. *Management Science* 65(2): 714–734.

Sunar N and Swaminathan JM (2021) Net-metered distributed renewable energy: A peril for utilities? *Management Science* 67(11): 6716–6733.

Wu O and Kapuscinski R (2013) Curtailing intermittent generation in electrical systems. *Manufacturing & Service Operations Management* 15(4): 578–595.

Würzburg K, Labandeira X and Linares P (2013) Renewable generation and electricity prices: Taking stock and new evidence for germany and austria. *Energy Economics* 40: S159–S171.

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