Prosumer Pricing, Incentives and Fairness

Ali Khodabakhsh, Jimmy Horn*, Evdokia Nikolova, Emmanouil Pountourakis
University of Texas at Austin *Horn Wind, LLC

ABSTRACT

Many current electricity rate structures for residential consumers do not provide proper incentives for consumer solar production. They also unfairly burden traditional consumers in favor of solar producing consumers ("prosumers"), by charging the bulk of utility internal operating costs to the rate-paying consumers. We propose a modified rate structure that first, more fairly divides the overhead cost among all customers, and second, provides proper incentives allowing the utility to control and to promote grid friendly solar producers that maximally benefit the entire customer base, which we call "positive prosumers." We also propose a mechanism that induces near truthful reporting of gross demand by prosumers, which is a needed input for our new rate structure.

CCS CONCEPTS

• **Hardware → Renewable energy**; *Smart grid*.

KEYWORDS

Solar generation, renewable energy technologies.

ACM Reference Format:
Ali Khodabakhsh, Jimmy Horn*, Evdokia Nikolova, Emmanouil Pountourakis. 2019. Prosumer Pricing, Incentives and Fairness. In *Proceedings of the Tenth ACM International Conference on Future Energy Systems (e-Energy '19), June 25–28, 2019, Phoenix, AZ, USA.* ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3307772.3328304

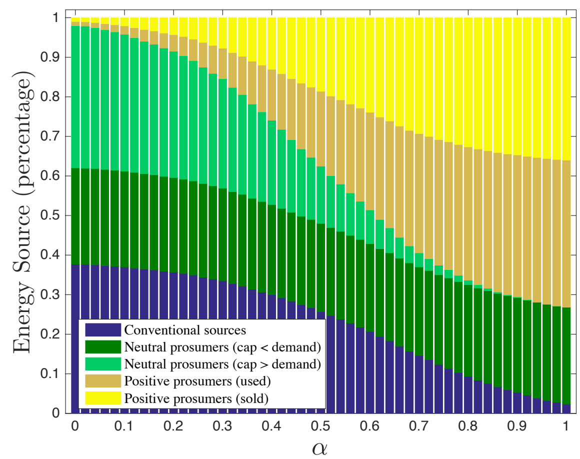

Figure 1: Energy sources versus α value *(the tuning parameter in our rate structure).*

1 INTRODUCTION

Many current electricity rate structures do not provide adequate incentives for customers to invest in solar production greater than their demand, and thus limit the positive effects renewable energy can provide. Prosumers currently have no incentive to invest in larger solar systems that can produce more than they consume. This is because they are able to save the energy, transmission, and a majority of overhead costs (~ 12 ¢/kWh) when they produce power up to their demand, but only receive the energy price (~ 4 ¢/kWh) for the power above their demand that they sell back to the utility. Thus they are not currently incentivized sufficiently to choose to produce power beyond their own consumption. Ideally, for reasons explained later in the paper, we would like each prosumer to produce more than their demand. We call such customers positive prosumers. We call "neutral prosumers" the customers who produce less than or equal to their demands, and thus do not sell any extra power back into the utility grid.

The overall goal of our new rate structure is to give utilities a mechanism to control and, if desired, to maximize the financial and grid benefit provided by each prosumer by promoting positive prosumers and, when possible, reducing the less beneficial neutral prosumers.

Fig. 1 shows the source of energy in different scenarios with different values of α, our tuning parameter. As α increases, i) neutral prosumers who can produce more than they use (light green) become positive prosumers (orange and yellow), and ii) the amount of energy the utility has to buy from outside sources (blue) is reduced.

Both positive and neutral prosumers create overhead costs, in part due to maintenance costs incurred by the utility's requirement to supply power to prosumers when their solar generation is not producing. Also in the upfront costs of new connection equipment, coupled with the additional failure risk of adding new or modified solar connections, which can cause overloads. The latter costs and risk make it desirable to have less solar connection points.

Balancing costs to all rate-payers is also an objective of this paper. In most current practices, the consumers pay a majority of the overhead cost due to prosumers only pay overhead on the power they purchase from the utility (and not on the power they produce), even though they utilize grid services for both. Overhead cost has a small fixed and a larger variable component, proportional to gross demand, meaning it also includes the prosumers' produced power (we define gross demand as total demand and net demand as gross demand less own production). This is because on a cloudy day, prosumers may also need to buy power from the utility; and it is the utility's job to guarantee supply in all situations. In this paper, we concentrate on the larger variable overhead cost ("overhead cost").

e-Energy '19, June 25–28, 2019, Phoenix, AZ, USA

ACM ISBN 978-1-4503-6671-7/19/06…$15.00
https://doi.org/10.1145/3307772.3328304

Ultimately under most current pricing structure, traditional consumers are paying for the backup power security and grid services utilized by prosumers.

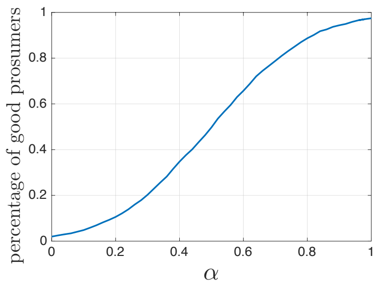

Figure 2: Positive prosumers (percentage) versus the value of α. *We exclude customers who are not capable of producing above their demand, since they cannot change.*

In this paper we propose a mechanism that fixes the above two issues, by first more evenly distributing the overhead cost to all customers based on their gross demand and second, by deriving a method to allow the utility to control the level of solar penetration, which in turn allows for a more stable system and a cheaper power rate to all rate-paying customers (see Fig. 3-(left)).

Our rate structure utilizes a factor α that the utility can adjust as desired to control solar penetration and the type of prosumers (positive or neutral). Fig. 1 shows how solar generation from positive prosumers, produced above their demand (yellow) replaces the more expensive outside power that needs to be purchased (blue) as α increases. Fig. 2 shows the number of positive prosumers as a function of α. As one can see, in both Fig. 1 and Fig. 2, as α increases, the percentage of positive prosumers increases and neutral prosumers decrease.

In Sections 3, 4, and 5 we explain current rate structure issues and our two-step alternative solution of: *balancing overhead costs* and then *promoting a more beneficial prosumer group.* In Section 6 we demonstrate the effectiveness of our proposed rate structure, and explain the settings of each figure in more detail. In Section 7 we propose a mechanism for near truthful reporting of gross demands.

2 RELATED WORK

Despite advances in renewable energy, several barriers still impede renewable penetration. A framework for analyzing the barriers has been proposed by Painuly [20], while Oliver and Jackson [19] focus on barriers to the deployment of solar photovoltaic (PV), and divide these barriers into technological [14], financial [17, 23], institutional [7], regulatory [14], and structural barriers [10]. Our work is most closely related to financial aspects, in which Pineda *et al.* [21] investigate the impact of different renewable support schemes (e.g., feed-in tariff, feed-in premium, trading of green certificates) on generation expansion decisions. Various papers study the design of feed-in tariffs [3, 4, 9, 16], but differ from our work in both their tariff structure and in them not considering a fairness criterion.

The problem of designing a fair payment scheme has been studied for renewable energy aggregation, which has been introduced as a solution to mitigate the variability of renewable supply [13, 15]. This is achieved by aggregating a diverse collection of resources. In the case of aggregation, a proper payment mechanism is needed to fairly distribute the payment from the system operator among the participants such that i) renewable producers have incentive to participate in the aggregation [18], ii) the payment mechanism stabilizes any coalition among participants [1, 2, 24], and iii) individuals are paid based on their actual production [13]. Since our main focus is on solar production (which does not meet the required negative correlation among generations), we do not consider aggregation in this paper. We note that community solar programs have also been studied in the literature [5].

When it comes to fairness, the increasing number of prosumers utilizing net-metering results in a shift of costs from prosumers to rate-paying consumers [6, 8]. Procter [22] raises the question of "How the utility's approach for recovering its fixed costs affects the economics of renewables." Granqvist and Grover [12] introduce four ethical principals that speak to different notions of fairness. Finally, Franklin and Osborne [11] study the implications of rooftop solar for energy justice through an urban political ecology approach.

In comparison to the above work, we propose a rate structure that addresses both incentive and fairness issues simultaneously.

3 RATE STRUCTURE FAIRNESS ISSUES

In many existing rate structures, the overhead cost is charged to each customer based on their net demand, although for improved fairness we propose it to be charged based on their gross demand. To model the existing rate structure, we assume $O = o \times \sum_{i=1}^{n} d_i$ is the total variable overhead cost, where d_i is the demand of customer i. Then each customer is charged as follows:

$$R(p_i, d_i) = \begin{cases} (d_i - p_i)(e+t) + \frac{d_i - p_i}{\sum_{j=1}^{n}[d_j - p_j]_+} \cdot O, & p_i < d_i \\ 0, & p_i = d_i \\ -(p_i - d_i)e, & p_i > d_i \end{cases}$$

where e, t are the electricity and transmission costs, p_i is the solar production of customer i, and $[x]_+ = \max\{x, 0\}$. Note that only power purchased from the utility is charged an overhead cost. Also, the customer's payment to the utility is negative if the customer produces more than their demand, since the utility buys the extra production at the fixed rate e. For example, assume we have two customers with $d_1 = 50$ kWh and $d_2 = 100$ kWh. Also assume that customer 1 produces $p_1 = 60$ kWh while customer 2 has no solar production. In this case, customer 1 will get paid for the extra 10 kWh sold to the grid, and customer 2 will have to pay for his demand used and for both customers' overhead costs. In other words, customer 1 does not incur any overhead cost, even though his gross demand is contributing to the total overhead cost O.

4 STEP 1: RATE RESTRUCTURING FOR FAIRNESS

To resolve the overhead issue, we propose a revised rate structure, which improves fairness to all the customers and allows the utility to charge overhead cost based on gross and not net demand. In our method, the utility would charge the customers as follows:

$$R(p_i, d_i) = \begin{cases} \frac{d_i}{\sum_{j=1}^{n} d_j} \cdot O + (d_i - p_i) \cdot r, & p_i < d_i \\ \frac{d_i}{\sum_{j=1}^{n} d_j} \cdot O, & p_i = d_i \\ \frac{d_i}{\sum_{j=1}^{n} d_j} \cdot O - (p_i - d_i)(e + \alpha t), & p_i > d_i \end{cases}$$

The main difference in our method is the overhead cost is now paid on all power used (from solar and the utility) regardless of the customers' production level. Although the gross demand is private information which the utility may not have access to, in Section 7 we propose a mechanism for near truthful self-reporting of gross demand by prosumers.

5 STEP 2: RATE RESTRUCTURING TO PROMOTE A BETTER PROSUMER GROUP

In our proposed method, the utility buys the solar power at an increased cost of $e + \alpha t$, compared to the previous cost of e. Additionally, all customers receive the billing rate r which is determined by the following equation, in a way so that the total cost of buying power from both the grid and prosumers equals the total amount billed to the customers.

$$r = \frac{(e + \alpha t) \sum_{i=1}^{n} [p_i - d_i]_+ + (e + t) \sum_{i=1}^{n} (d_i - p_i)}{\sum_{i=1}^{n} [d_i - p_i]_+} \quad (1)$$

The numerator in equation (1) is the total price the utility pays to buy power from both the transmission side and prosumers, while the denominator is the amount of power sold to all customers.

In our proposed rate structure, we assume that the gross demands of customers (d_i's) are known to the utility, while the solar production levels (p_i's) are strategic decisions by the customers. Since the overhead portion of the payment in Step 1 is now independent of production, the customers will follow this simple rule:

$$p_i = \begin{cases} 0, & c_i \geq r \\ \min\{d_i, p_i^{\max}\}, & r > c_i \geq e + \alpha t \\ p_i^{\max}, & e + \alpha t > c_i \end{cases}$$

To explain the above, when a customer's production cost c_i is higher than the rate r, he will choose not to be a prosumer. When his c_i is less than r but greater than $e + \alpha t$, he will be a neutral prosumer, only producing up to his demand d_i. And lastly when a customer's c_i is less than both r and $e + \alpha t$, he will produce as much as he can (i.e., up to his production limit $p_i^{\max}$). Therefore by increasing the value of α, we provide incentive for prosumers to produce more than their demand and thus become positive prosumers.

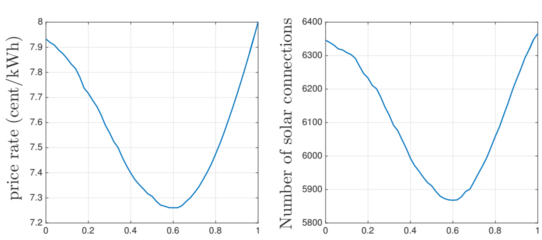

Figure 3: Rate r and solar connections versus the α value.

In Fig. 3-(left), we have plotted the rate as defined in equation (1). It can be shown that this rate will always settle between the prosumer selling price of $e + \alpha t$ and the transmission grid buying cost of $e + t$. As α is increased from zero to one, the utility obtains more power from prosumer solar production, which is a cheaper source than from the transmission grid. When α reaches its maximum of one, the price of solar energy becomes equal to the transmission grid, at $e + t$. With our method, the addition of more prosumers will never increase the overall cost to the system, and thus **always provides a lower rate for the rate-paying customers.** The minimum rate r shown in Fig. 3-(left) is achieved at a point when α is high enough to entice a large portion of customers to become positive prosumers, but still low enough that the marginal benefit added by each new prosumer is greater than the increase in the total $e + \alpha t$ cost paid to all current prosumers.

Fig. 3-(right) shows the number of solar connection points versus the value of α. Since the customers have a pre-set production cost (c_i) and will become prosumers when and only when their production cost is below the rate r, the number of connections will follow r and decrease as r decreases. This is justified by the strong correlation between the rate and connection curves in Fig. 3.

6 SIMULATIONS

Table 1: Nomenclature

Parameter	Description
e	Electricity cost (¢/kWh).
t	Transmission cost (¢/kWh).
o	Overhead cost (¢/kWh).
r	Billing rate (¢/kWh)
c_i	Production cost of i^{th} user (¢/kWh).
p_i	Production level of i^{th} user (kWh/month).
d_i	Gross demand of i^{th} user (kWh/month).
$p_i^{\max}$	Production limit of i^{th} user (kWh/month).
n	Number of customers.

We consider a grid with $n = 10,000$ customers, and generate the parameters according to the distributions described below to resemble a real-world scenario.

Grid costs: We set the electricity, transmission, and overhead costs to each be equal $e = t = o = 4$ ¢/kWh.

Renewable generation cost: Independently for each customer, we draw a random cost $c_i \sim \mathcal{N}(\frac{3}{2}e, 1)$, where $\mathcal{N}(\mu, \sigma^2)$ is the normal distribution with mean μ and variance σ^2. If c_i happens to be less than $\frac{3}{4}e$, we set it to $\frac{3}{4}e$ (i.e., no customer is able to produce power for less than 3 ¢/kWh).

Customer demands: For each customer we draw a random demand d_i uniformly from the interval $[d_{min}, d_{max}]$, where $d_{min} = 0.4 \times d_{avg}$ and $d_{max} = 1.6 \times d_{avg}$; also $d_{avg} = 1000$ kWh/month is the average residential demand (i.e., each customer can be up to 60% below or above the average).

Production limits: First we set $p_i^{\max} = 0$ for 35% of the customers, so as to simulate the population who do not believe in renewable energy, or do not have access to a rooftop to install solar panels. For the rest of population, we make the assumption that both demand

and solar production limit are related to the square footage of the building. Considering this correlation, we cannot randomly select the production limits $p_i^{\max}$. Instead, we set $p_i^{\max} = k \times d_i$, for a constant k that we explain how to choose below. Notice that if a customer lives in a building with n_s stories, he can use up to $1/n_s$ of this production limit, so we refine the equation to $p_i^{\max} = k \times d_i / n_s$. We pick n_s randomly from 1 to 4 according to the probability mass function $\{0.40, 0.30, 0.20, 0.10\}$ (i.e., 40% being one story buildings, 30% two story, etc.) We assume that people in buildings with more than 4 stories, belong to that 35% who do not have or chose not to use their rooftops for solar. Finally we pick a constant k such that the aggregate production limit $\sum_i p_i^{\max}$ does not exceed the total demand $\sum_i d_i$. The reason is that once this limit is exceeded, excess solar production would have to be sold back to the transmission grid. This is possible but outside the scope of our analysis. Additionally, the aggregate production limit can be set anywhere below the total demand.

7 INCENTIVES UNDER INCOMPLETE INFORMATION

Our proposed rate structure in Section 4 is based on full information of the gross demands, which are not necessarily available to the utility. Note that reporting the gross demand is equivalent to reporting the solar production, as the utility measures the net demand and can calculate the third parameter once two of them are known. If customers can choose, they will report the minimum amount of solar production (i.e., zero), so as to pretend that their gross demand is equal to their net demand (measured by the utility) and no more. In this way, they are able to minimize their payment. We next investigate how the utility can induce truthfulness by introducing a penalty for inconsistent reporting.

For simplicity of explanation, consider a time horizon of two rounds (e.g., two months) and also assume that the customer's gross demand is constant across these rounds (we explain in Appendix A how to relax this assumption). Now the utility charges an additional penalty of $\gamma.O.|d_i^1 - d_i^2|$ to each user i, where γ is a constant (the penalty rate), O is the total overhead cost, and d_i^1, d_i^2 are the reported gross demands of customer i in rounds one and two, respectively.

Let d_i denote the actual gross demand (in both rounds), and p_i^1, p_i^2 be the solar productions in these rounds. Note that previously, p_i was a long-term investment variable, but now p_i^1, p_i^2 are short-term variables which change due to weather conditions, though are upper bounded by the installed capacity p_i. When $\gamma = 0$, the customer will report $d_i^1 = d_i - p_i^1$ according to the previous discussion. As we increase γ, there is a chance that the customer will not be able to produce as much power in the next round (i.e., $p_i^2 < p_i^1$). In that case, he has to report a larger gross demand $d_i^2 = d_i - p_i^2 > d_i^1$ and therefore would have to pay the extra penalty.

As a result, the customer will consider the trade-off between reporting a small gross demand to minimize their current bill, versus being truthful and avoiding the penalty across multiple time steps. A reasonable behavior for a customer is to minimize their expected total payment. So, as we increase the penalty rate (γ), the truthfulness becomes more dominant and the customer reports move closer to their actual gross demands. This is shown in Figure 4 (blue curve), for a synthetic scenario with 100 customers creating a total demand of 100 MWh/month and a particular customer i with $d_i = p_i = 1000$ kWh per month. This figure shows the behaviour of this customer, once he produces $p_i^1 = 500$ kWh in the first month. We assume a uniform production p_i^2 for his second month. Defining the cheating level as the difference between the reported and true gross demands, the curve shows that the customer becomes more truthful as the penalty rate increases.

Finally, we argue that the customers become even more truthful as the number of rounds increases. Roughly speaking, this is due to the more uncertainly in future production levels and the fact that with more rounds, there is more chance of their fabricated report being caught by the utility. Therefore, we can achieve near truthfulness with even small rates of penalty (γ), because the number of rounds in a real scenario could be practically infinite.

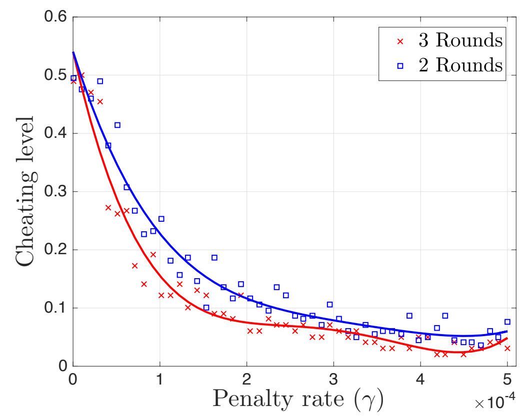

Figure 4: Cheating level versus the penalty rate γ. Each line is a fitted curve of degree 4 to the corresponding data points.

This phenomenon is shown in Figure 4, where we plot the cheating levels for 2 and 3 rounds, for every value of penalty rate γ. It can be seen that for a fixed value of γ, as we add an additional round, the customer becomes more truthful. Since the number of samples required to compute the expected payment grows exponentially as we increase the number of rounds, it is computationally infeasible to produce the corresponding plot for more rounds. However, considering the typical monotonicity of such behaviours, we conjecture that this trend continues as we increase the number of rounds. We aim to prove this analytically, in the full version of this paper.

8 CONCLUSION

We introduce a new rate structure for electricity customers that, compared to most existing practices, more fairly divides the overhead costs among the customer base (either consumer or prosumer) and provides the utility a mechanism to control solar penetration. This extra production in turn lowers the overall rate for all rate-paying customers. By adjusting a single parameter (α) in our rate structure, we can i) achieve the optimal lowest rate r for the customer base, ii) promote beneficial solar producing customers, and iii) reduce system risk by minimizing the total number of solar connection points. We feel our rate structure can allow utilities to optimize customer rates while still both solidifying their rate-payer base and strengthening their infrastructure stability.

REFERENCES

[1] Enrique Baeyens, EY Bitar, Pramod P Khargonekar, and Kameshwar Poolla. 2011. Wind energy aggregation: A coalitional game approach. In *Decision and Control and European Control Conference (CDC-ECC), 2011 50th IEEE Conference on*. IEEE, 3000–3007.

[2] Eilyan Y Bitar, Enrique Baeyens, Pramod P Khargonekar, Kameshwar Poolla, and Pravin Varaiya. 2012. Optimal sharing of quantity risk for a coalition of wind power producers facing nodal prices. In *American Control Conference (ACC), 2012*. IEEE, 4438–4445.

[3] Trine Krogh Boomsma, Nigel Meade, and Stein-Erik Fleten. 2012. Renewable energy investments under different support schemes: A real options approach. *European Journal of Operational Research* 220, 1 (2012), 225–237.

[4] Lucy Butler and Karsten Neuhoff. 2008. Comparison of feed-in tariff, quota and auction mechanisms to support wind power development. *Renewable energy* 33, 8 (2008), 1854–1867.

[5] Gabriel Chan, Matthew Grimley, Ben Ihde, and Isaac Evans. 2017. The Political Economy of Community Solar: Lessons from Minnesota. In *Riding the Energy Cycles, 35th USAEE/IAEE North American Conference, Nov 12-15, 2017*. International Association for Energy Economics.

[6] R Cohen. 2013. The giant headache that is net energy metering. *The Electricity Journal* (2013), 1–7.

[7] Pablo Del Río and Gregory Unruh. 2007. Overcoming the lock-out of renewable energy technologies in Spain: the cases of wind and solar electricity. *Renewable and Sustainable Energy Reviews* 11, 7 (2007), 1498–1513.

[8] Cherrelle Eid, Javier Reneses Guillén, Pablo Frías Marín, and Rudi Hakvoort. 2014. The economic effect of electricity net-metering with solar PV: Consequences for network cost recovery, cross subsidies and policy objectives. *Energy Policy* 75 (2014), 244–254.

[9] Riccardo Fagiani, Julián Barquín, and Rudi Hakvoort. 2013. Risk-based assessment of the cost-efficiency and the effectivity of renewable energy support schemes: Certificate markets versus feed-in tariffs. *Energy policy* 55 (2013), 648–661.

[10] Timothy J Foxon, R Gross, A Chase, J Howes, Alex Arnall, and David Anderson. 2005. UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures. *Energy policy* 33, 16 (2005), 2123–2137.

[11] Remington Santiago Franklin and Tracey Osborne. 2017. Toward an urban political ecology of energy justice: the case of rooftop solar in Tucson, AZ. *Journal of Political Ecology* 24, 1 (2017), 1055–1076.

[12] Harry Granqvist and David Grover. 2016. Distributive fairness in paying for clean energy infrastructure. *Ecological Economics* 126 (2016), 87–97.

[13] Farshad Harirchi, Tyrone Vincent, and Dejun Yang. 2014. Optimal payment sharing mechanism for renewable energy aggregation. In *Smart Grid Communications (SmartGridComm), 2014 IEEE International Conference on*. IEEE, 608–613.

[14] Emrah Karakaya and Pranpreya Sriwannawit. 2015. Barriers to the adoption of photovoltaic systems: The state of the art. *Renewable and Sustainable Energy Reviews* 49 (2015), 60–66.

[15] Hossein Khazaei and Yue Zhao. 2017. Ex-post stable and fair payoff allocation for renewable energy aggregation. *Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)* (2017), 1–5.

[16] Jonathan A Lesser and Xuejuan Su. 2008. Design of an economically efficient feed-in tariff structure for renewable energy development. *Energy policy* 36, 3 (2008), 981–990.

[17] Philippe Menanteau, Dominique Finon, and Marie-Laure Lamy. 2003. Prices versus quantities: choosing policies for promoting the development of renewable energy. *Energy policy* 31, 8 (2003), 799–812.

[18] Ashutosh Nayyar, Kameshwar Poolla, and Pravin Varaiya. 2013. A statistically robust payment sharing mechanism for an aggregate of renewable energy producers. In *Control Conference (ECC), 2013 European*. IEEE, 3025–3031.

[19] M Oliver and Thomas Jackson. 1999. The market for solar photovoltaics. *Energy Policy* 27, 7 (1999), 371–385.

[20] Jyoti P Painuly. 2001. Barriers to renewable energy penetration; a framework for analysis. *Renewable energy* 24, 1 (2001), 73–89.

[21] Salvador Pineda, Trine K Boomsma, and Sonja Wogrin. 2018. Renewable generation expansion under different support schemes: A stochastic equilibrium approach. *European Journal of Operational Research* 266, 3 (2018), 1086–1099.

[22] Robert J Procter. 2014. Fixed-cost recovery, renewables adoption and rate fairness. *The Electricity Journal* 27, 5 (2014), 42–53.

[23] Carlos Vargas and Marc Chesney. 2018. What are You Waiting to Invest? Long-Term Investment in Grid-Connected Residential Solar Energy in California. A Real Options Analysis. *Renewable and Sustainable Energy Reviews* (2018).

[24] Baosen Zhang, Ramesh Johari, and Ram Rajagopal. 2015. Competition and coalition formation of renewable power producers. *IEEE Transactions on Power Systems* 30, 3 (2015), 1624–1632.

ACKNOWLEDGMENTS

The authors would like to thank the anonymous referees for their valuable feedback. We gratefully acknowledge the financial support from NSF under grants CCF-1733832, CCF-1331863, and CCF-1350823.

A CORRELATION AMONG CUSTOMERS

In Section 7 we assumed that the gross demands d_i of the customers are constant in the two round instance. We can generalize this assumption to situations where the gross demand may change after each period but the percentage of change is common across all customers. The utility observes the rest of the population and finds the average percentage change in gross demands. Then it calculates the gross demand that a given customer should have that period (based on the customer's previous reports) and computes the penalty according to it.