Title

Analysis of Solar Energy Aggregation Under Various Billing Mechanisms

Journal

IEEE Transactions on Smart Grid, 10(4)

ISSN

1949-3053

Authors

Chakraborty, Pratyush
Baeyens, Enrique
Khargonekar, Pramod P
et al.

Publication Date

2019-07-01

DOI

10.1109/tsg.2018.2851512

Analysis of Solar Energy Aggregation under Various Billing Mechanisms

Pratyush Chakraborty, Enrique Baeyens, and Pramod P. Khargonekar

***Abstract*—Ongoing reductions in the cost of solar photovoltaic (PV) systems are driving increased residential households installations. Various incentive programs such as feed-in tariff, net metering, net purchase and sale that allow the consumers to sell their generated electricity to the grid are also powering this trend. In this paper, we investigate sharing of PV systems among a set of households who can also benefit further by pooling their production. We first find conditions under which such sharing decreases their net total cost. Next, we develop allocation rules such that the joint net electricity consumption cost is allocated to the participants based on cost causation principle. The joint cost also satisfies standalone cost principle thus promoting PV solar aggregation.**

***Index Terms*—Solar PV aggregation, Net metering, Net purchase and Sale, Cost allocation based on cost causation , Cooperative games**

I. Introduction

Greater adoption of residential scale solar photovoltaic renewable electric energy is a compelling engineering and sustainability objective. Due to ongoing price reductions [1], various types of subsidies [2], and desire to decarbonize the energy system [3], there has been dramatic increase in rooftop solar PV installations. As residential users install rooftop solar panels and generate portions of their electricity needs, the need for fossil fuel based electric plants decreases. The total PV installations globally have reached 300 GW by 2016 [4] of which about 28% are decentralized grid connected. We are interested in developing techniques and tools that can further increase the cost-effectiveness of rooftop solar PV installations.

There exist three main billing programs around the world that enable homeowners to sell their PV electricity to the grid: feed-in-tariff, net metering, and net purchase and sale [5]. Some utilities consider these programs as a threat to their business models [6]. On the other hand, socio-economic-environmental policies surrounding climate change have motivated various governments to encourage such programs.

In this paper, we investigate how sharing the electricity generated by rooftop PV in a cooperative manner can further facilitate their adoption by decreasing overall energy costs. We assume that the rooftop solar panels are electrically connected with each other and the necessary hardware for electricity sharing has been installed. Sharing economy has been a huge success in housing and transportation sectors in recent times [7]. It has been propelled by the desire to leverage under-utilized infrastructures in existing houses and cars. Companies like Uber, Lyft, AirBnB, VRBO made large impacts in transportation and housing sectors [8]. In the electricity sector, there are literature of modeling resource sharing. Cooperation and aggregation of renewable energy sources bidding in the two settlement market to maximize expected and realized profit has been analyzed using cooperative game theory [9], [10]. Cooperative game theoretic analysis of multiple demand response aggregators in a virtual power plant and their cost allocation has been tackled in [11]. Sharing of storage firms under a local spot market has been analyzed using non-cooperative game theory [12].

To the best of our knowledge, sharing of PV systems among different houses under various billing schemes has not been investigated. Can sharing of rooftop PV electricity reduce costs to consumers under various billing mechanisms? If the answer is affirmative, to encourage and preserve cooperative sharing, it will be crucial to have just and reasonable allocation of the resulting cost reduction or benefit increase to the participating individuals. These are precisely the questions we analyze in this paper.

Our results show that there is no advantage to cooperation in the case of feed-in tariff, an intuitively clear conclusion. We derive a necessary and sufficient condition on pricing under which cooperation is beneficial for the participating consumers in net metering, and net purchase and sale mechanisms. Under this pricing condition, we develop rules for allocating joint cost based on cost causation principle [10]. The allocation rules also follow standalone cost principle, *i.e.* they are in the core of cooperative games of net electricity consumption costs. These results provide theoretical basis for sharing of rooftop PV generation among consumers. We present a case study based on real consumption and generation data to illustrate the results.

The remainder of the paper is organized as follows. In Section II, we formulate the problem with notations. In Section III, we describe our previous results on cost allocation based on cost causation. In Section IV, we derive our main results. The case study is in Section V. Finally, conclusions are presented in Section VI.

II. Problem formulation

Consider a set of $\mathcal{N} = \{1, 2, \dots, N\}$ households with PV systems. The price of electricity designed by the utility from the grid to households is λ. The households can sell

This work is supported in part by NSF grants ECCS-1129061 and CNS-1239274

Pratyush Chakraborty is with the Department of Mechanical Engineering, University of California, Berkeley, CA, USA pchakraborty@berkeley.edu

Enrique Baeyens is with Instituto de las Tecnologías Avanzadas de la Producción, Universidad de Valladolid, Valladolid, Spain enrbae@eis.uva.es

Pramod P. Khargonekar is with the Department of Electrical Engineering and Computer Science, University of California, Irvine, CA, USA pramod.khargonekar@uci.edu

their power to the grid at a price μ. We consider three programs: feed-in tariff, net metering, and net purchase and sale that allow houses to sell their generated electricity to the grid. These three mechanisms are explained in detail in [5], indicating their countries of usage and also analyzing their impact on social welfare.

We assume here that households obtain more utility than their cost for solar generation and thus rationally install solar panels.

In *feed-in tariff* method, the households can sell all of their PV generation at price μ and they must purchase all of their consumed electricity from the grid at price λ. In contrast, under the programs net metering, and net purchase and sale systems, electric utility of the grid purchases only the net amount of the PV generation of the households that exceeds their consumption. But the two programs compute their net in different ways. In *net metering*, when the PV generation of a household exceeds its consumption, the electric meter runs backward. At the end of a billing period, if the amount of electricity generation is more than consumption, the household is paid for the net PV generation at price μ. If the amount of electricity generation is less than consumption, the household has to pay the net amount consumed at price λ. In *net purchase and sale*, the generation and consumption is compared at each time and the PV generated electricity is fed into the system actually when generation exceeds consumption and purchased by the utility at price μ. Otherwise, the consumed electricity is purchased by the household at price λ. So the amount of electricity is compared moment by moment in this program instead of at the end of a billing period in net metering.

Let us consider a billing period $[t_0, t_f]$ of duration $T = t_f - t_0$. For the i-th household at time $t \in [t_0, t_f]$, let the electricity consumption be $q_i(t)$, and the generation by rooftop solar panels be $g_i(t)$.

The net electricity consumption cost of the household for the entire billing period is:

$$C_i = \lambda Q_i - \mu G_i, \tag{1}$$

where Q_i and G_i are the i-th household's energy consumption and generation during the billing period, respectively. These quantities are computed in a different way depending on the billing mechanism.

For *feed-in tariff* mechanism:

$$Q_i = \int_{t_0}^{t_f} q_i(t)dt, \quad G_i = \int_{t_0}^{t_f} g_i(t)dt. \tag{2}$$

For *net metering* mechanism:

$$Q_i = \left(\int_{t_0}^{t_f} q_i(t)dt - \int_{t_0}^{t_f} g_i(t)dt \right)_+, \tag{3}$$

$$G_i = \left(\int_{t_0}^{t_f} g_i(t)dt - \int_{t_0}^{t_f} q_i(t)dt \right)_+. \tag{4}$$

For *net purchase and sale* mechanism:

$$Q_i = \int_{t_0}^{t_f} (q_i(t) - g_i(t))_+ dt, \tag{5}$$

$$G_i = \int_{t_0}^{t_f} (g_i(t) - q_i(t))_+ dt. \tag{6}$$

Note that the net consumption for each household $i \in \mathcal{N}$ is obtained as $D_i = Q_i - G_i$ and is the same for the three billing mechanisms, but the cost C_i is different and depends on the billing mechanism.

Let $\mathcal{S} \subseteq N$ denote a coalition of households that decide to cooperate to share their electricity generation by rooftop solar panels and save electricity costs. We assume that the rooftop solar panels are electrically connected with each other and the houses also have necessary hardwares for electricity sharing. The total energy consumption and generation of the coalition for the interval $[t_0, t_f]$ are denoted as $Q_\mathcal{S}$ and $G_\mathcal{S}$, respectively. The consumption is charged at price λ and the generation is paid at price μ. Consequently, the cost of the coalition for the time interval $[t_0, t_f]$ is

$$C_\mathcal{S} = \lambda Q_\mathcal{S} - \mu G_\mathcal{S}, \tag{7}$$

where the expressions of $Q_\mathcal{S}$ and $G_\mathcal{S}$ depend on the billing program.

III. Previous Results on Cost Causation Based Allocation

In this section, we will summarize our previous results on cost causation based allocation [10], [13].

We proposed in [10] five axioms that characterize *just and reasonable* allocation rules. These axioms are: *equity*, *monotonicity*, *individual rationality*, *budget balance*, and *standalone cost principle*.

Let us consider a set of customers $\mathcal{N}$ that consume electricity and can also generate electricity using their PV solar panels. A coalition $\mathcal{S} \subseteq \mathcal{N}$ represents a group of customers that decide to act as an entity and jointly pay the electricity bill. The cost of each coalition $\mathcal{S}$ is a function of the net consumption $D_\mathcal{S}$ during the time interval $[t_0, t_f]$ and is denoted by $C_\mathcal{S}$. Coalition formation is promoted if the cost of a coalition is lower than the sum of the individual costs of the members. Let us begin by defining the concept of successful cooperation.

Definition 1: A group $\mathcal{N}$ of households can achieve successful cooperation if the cost function is subadditive for the set union operation.

If the group $\mathcal{N}$ achieves successful cooperation, then for any two disjoint subsets, $(\mathcal{S}, \mathcal{T}) \subseteq \mathcal{N} \times \mathcal{N}$

$$C_{\mathcal{S} \cup \mathcal{T}} \leq C_\mathcal{S} + C_\mathcal{T}. \tag{8}$$

This means that the coalition formation may produce a cost reduction.

A cost allocation for a coalition $\mathcal{S} \subseteq \mathcal{N}$ is a distribution of the coalition cost $C_\mathcal{S}$ among the members of the coalition.

Definition 2 (Cost allocation rule): Let $\mathcal{N}$ be a set of consumers that aggregate to share net consumption cost. A cost allocation is a vector $\{x_i : i \in \mathcal{S}\}$ such that x_i represents the cost allocated to each consumer $i \in \mathcal{N}$.

A cost allocation can be evaluated by analyzing its properties. We define an axiomatic framework to characterize the key desirable properties of a cost allocation rule.

Axiom 1 (Equity): If two agents i and j have same net consumptions the allocated costs must be the same *i.e.*, if $D_i = D_j$ then $x_i = x_j$.

Axiom 2 (Monotonicity): If two agents i and j have net consumptions of the same sign, and agent i has a higher net consumption than agent j, then the absolute value of the allocated cost to i must be higher than the absolute value of the allocated cost to j *i.e.*, if $D_i D_j \geq 0$ and $|D_i| \geq |D_j|$ then $|x_i| \geq |x_j|$.

Axiom 3 (Individual Rationality): The allocated cost must be less than the cost if the agent would not have joined the aggregation *i.e.*, $x_i \leq C_i$.

Axiom 4 (Budget Balance): The cost allocation rule would be such that the sum of allocated costs must be equal to the net electricity consumption cost *i.e.*, $\sum_{i \in N} x_i = C_{\mathcal{N}}$.

Axiom 5 (Standalone Cost Principle): For every coalition $\mathcal{S} \subset \mathcal{N}$,

$$\sum_{i \in S} x_i \leq C_{\mathcal{S}}. \tag{9}$$

A cost causation based allocation as proposed by [14] should follow the general axioms of equity, monotonicity, individual rationality and budget balance, but not necessarily the standalone cost principle. However, not every allocation rule satisfying these four axioms follows the cost causation principle, because they do not explicitly take into account whether agents are causing or mitigating costs.

In order to characterize cost causation based allocations, we define who is causing and mitigating cost. Here $D_i = Q_i - G_i$ being the difference of Q_i and G_i a natural choice for the cause or mitigation variable for cost.

Definition 3 (Cost causation and mitigation): Let $D_{\mathcal{N}}$ be the net consumption of a group $\mathcal{N}$ of agents. It is said that agent i is causing cost if $D_i > 0$, and is mitigating cost if $D_i < 0$.

Based on this definition, we introduce two new cost causation based axioms: *penalty for cost causation* and *reward for cost mitigation*.

Axiom 6 (Penalty for causing cost): Those individuals causing cost should pay for it, *i.e.* $x_i > 0$ for any $i \in \mathcal{N}$ such that $D_i > 0$.

Axiom 7 (Reward for cost mitigation): Those individuals mitigating cost should be rewarded, *i.e.* $x_i < 0$ for any $i \in \mathcal{N}$ such that $D_i < 0$.

Using the previously introduced axioms, a *cost causation based* allocation rule is formally defined as follows:

Definition 4 (Cost causation based allocation rule): A cost allocation rule is said to be a *cost causation based allocation* rule if it satisfies Axioms 1–4 and 6–7.

If the cost sharing problem can be modeled as a balanced cooperative game, then any allocation in the core of the game satisfies the standalone cost principle. In fact, the core is the set of all allocations satisfying the axioms of *budget balance* and *standalone cost principle*. Thus, a stabilizing cost allocation can be equivalently defined in an axiomatic way as follows.

Definition 5 (Stabilizing cost allocation rule): A cost allocation rule is said to be stabilizing if it satisfies the axioms of *budget balance* and *standalone cost principle*.

It is interesting to remark that some well-known allocation rules such as the *proportional rule*, or the *Shapley value*, do not satisfy the cost causation principle.

IV. Main Results on Aggregation

In this section, we present the main results about cooperation of households for different billing programs. We study the conditions for each billing program to provide successful cooperation.

A. Feed-in tariff

For the coalition $\mathcal{S}$, under the feed-in tariff program, the net consumption is $D_{\mathcal{S}} = Q_{\mathcal{S}} - G_{\mathcal{S}}$ where

$$Q_{\mathcal{S}} = \sum_{i \in \mathcal{S}} Q_i, \quad G_{\mathcal{S}} = \sum_{i \in \mathcal{S}} G_i, \tag{10}$$

and Q_i, G_i are given by equations (2).

Let us consider two disjoint coalitions $\mathcal{S}$ and $\mathcal{T}$. For this billing program, the cost of the coalition $\mathcal{S}$ is

$$C_{\mathcal{S}} = \lambda Q_{\mathcal{S}} - \mu G_{\mathcal{S}}. \tag{11}$$

It is easy to see that $C_{\mathcal{S}} + C_{\mathcal{T}} = C_{\mathcal{S} \cup \mathcal{T}}$. So cooperation is neutral, there is no advantage or harm in cooperating and sharing the PV generation.

B. Net Metering

For the coalition $\mathcal{S}$, under the net metering program, the net consumption is $D_{\mathcal{S}} = Q_{\mathcal{S}} - G_{\mathcal{S}}$ where

$$Q_{\mathcal{S}} = \left(\sum_{i \in \mathcal{S}} \int_{t_0}^{t_f} q_i(t) dt - \sum_{i \in \mathcal{S}} \int_{t_0}^{t_f} g_i(t) dt \right)_+, \tag{12}$$

$$G_{\mathcal{S}} = \left(\sum_{i \in \mathcal{S}} \int_{t_0}^{t_f} g_i(t) dt - \sum_{i \in \mathcal{S}} \int_{t_0}^{t_f} q_i(t) dt \right)_+. \tag{13}$$

The cost for any coalition $\mathcal{S} \subseteq \mathcal{N}$ is

$$C_{\mathcal{S}} = \lambda Q_{\mathcal{S}} - \mu G_{\mathcal{S}}. \tag{14}$$

Theorem 1: The households will have successful cooperation if and only if $\lambda \geq \mu$.

Proof: Let us consider two disjoint coalitions $\mathcal{S}$ and $\mathcal{T}$, then

$$C_{\mathcal{S} \cup \mathcal{T}} = \lambda Q_{\mathcal{S} \cup \mathcal{T}} - \mu G_{\mathcal{S} \cup \mathcal{T}},$$

where

$$Q_{\mathcal{S} \cup \mathcal{T}} = (Q_{\mathcal{S}} + Q_{\mathcal{T}} - G_{\mathcal{S}} - G_{\mathcal{T}})_+,$$
$$G_{\mathcal{S} \cup \mathcal{T}} = (G_{\mathcal{S}} + G_{\mathcal{T}} - Q_{\mathcal{S}} - Q_{\mathcal{T}})_+,$$

and

$$C_{\mathcal{S}} + C_{\mathcal{T}} = \lambda (Q_{\mathcal{S}} + Q_{\mathcal{T}}) - \mu (G_{\mathcal{S}} + G_{\mathcal{T}}).$$

In net metering mechanism $Q_{\mathcal{S}} \geq 0$, $G_{\mathcal{S}} \geq 0$, and one of them is zero, *i.e.* $Q_{\mathcal{S}} G_{\mathcal{S}} = 0$ for any coalition $\mathcal{S} \subseteq \mathcal{N}$. Then we can distinguish four possible cases:

Case (I): $G_{\mathcal{S}} = G_{\mathcal{T}} = 0$,

$$C_{\mathcal{S} \cup \mathcal{T}} = \lambda (Q_{\mathcal{S}} + Q_{\mathcal{T}}) = C_{\mathcal{S}} + C_{\mathcal{T}}.$$

Case (II): $Q_{\mathcal{S}} = Q_{\mathcal{T}} = 0$,

$$C_{\mathcal{S} \cup \mathcal{T}} = -\mu (G_{\mathcal{S}} + G_{\mathcal{T}}) = C_{\mathcal{S}} + C_{\mathcal{T}}.$$

Case (III): $G_{\mathcal{S}} = Q_{\mathcal{T}} = 0$,

$$C_{\mathcal{S}\cup\mathcal{T}} = \lambda(Q_{\mathcal{S}} - G_{\mathcal{T}})_+ - \mu(G_{\mathcal{T}} - Q_{\mathcal{S}})_+,$$
$$C_{\mathcal{S}} + C_{\mathcal{T}} = \lambda Q_{\mathcal{S}} - \mu G_{\mathcal{T}}.$$

We have two cases, either $Q_{\mathcal{S}} \geq G_{\mathcal{T}}$ or $Q_{\mathcal{S}} < G_{\mathcal{T}}$. In both cases, $C_{\mathcal{S}\cup\mathcal{T}} \leq C_{\mathcal{S}} + C_{\mathcal{T}}$ if and only if $\mu \leq \lambda$.

Case (IV): $Q_{\mathcal{S}} = G_{\mathcal{T}} = 0$,

$$C_{\mathcal{S}\cup\mathcal{T}} = \lambda(Q_{\mathcal{T}} - G_{\mathcal{S}})_+ - \mu(G_{\mathcal{S}} - Q_{\mathcal{T}})_+,$$
$$C_{\mathcal{S}} + C_{\mathcal{T}} = \lambda Q_{\mathcal{T}} - \mu G_{\mathcal{S}}.$$

We have two cases, either $Q_{\mathcal{T}} \geq G_{\mathcal{S}}$ or $Q_{\mathcal{T}} < G_{\mathcal{S}}$. In both cases, $C_{\mathcal{S}\cup\mathcal{T}} \leq C_{\mathcal{S}} + C_{\mathcal{T}}$ if and only if $\mu \leq \lambda$.

Thus, cooperation is beneficial if and only if $\lambda \geq \mu$. □

The condition $\lambda \geq \mu$ is indeed justified because the price of consuming electricity should include generation, transmission and distribution costs. But transmission and distribution costs are not included in the price that the utility should pay to a consumer having solar PV systems for her generated electricity [15].

Under this scenario, we develop a cost allocation for the group members as follows.

Allocation 1 (Net metering): Let the allocated cost for the i-th household be x_i.

$$x_i = \begin{cases} \lambda D_i, & \text{if } D_{\mathcal{N}} \geq 0, \\ \mu D_i, & \text{if } D_{\mathcal{N}} < 0. \end{cases} \tag{15}$$

Theorem 2: The allocation defined by (15) is a cost causation based allocation.

Proof: According to Definition 4, we have to prove that the cost allocation rule given by (15) satisfies the Axioms 1–4 and 6–7. Let $D_i = Q_i - G_i$ be the net consumption. The allocation follows the following axioms:

Axiom 1 (Equity): It is easy to see that if two households i and j have same net consumptions, the allocated costs must be the same *i.e.*, if $D_i = D_j$ then $x_i = x_j$.

Axiom 2 (Monotonicity): Under the cost allocation rule (15), if $D_i D_j \geq 0$ and $|D_i| \geq |D_j|$ then $|x_i| \geq |x_j|$ and this proves Monotonicity.

Axiom 3 (Individual Rationality):

$$C_i = \begin{cases} \lambda Q_i, & \text{if } D_i \geq 0, \\ -\mu G_i, & \text{if } D_i < 0. \end{cases} \tag{16}$$

As $\lambda \geq \mu$, comparing (15) with (16) we can say that the allocated cost will be less than the net consumption cost if the household would not have joined the aggregation *i.e.*, $x_i \leq C_i$.

Axiom 4 (Budget Balance):

If $D_{\mathcal{N}} \geq 0$:

$$\sum_{i\in\mathcal{N}} x_i = +\sum_{i\in\mathcal{N}} \lambda(Q_i - G_i) = C_{\mathcal{N}}, \tag{17}$$

If $D_{\mathcal{N}} < 0$:

$$\sum_{i\in\mathcal{N}} x_i = -\sum_{i\in\mathcal{N}} \mu(G_i - Q_i) = C_{\mathcal{N}}. \tag{18}$$

So the cost allocation rule is such that the sum of allocated costs are equal to the total net electricity consumption cost *i.e.*,

$$\sum_{i\in\mathcal{N}} x_i = C_{\mathcal{N}}. \tag{19}$$

Recall from Definition 3 that a household i with positive net consumption $D_i = Q_i$ is causing cost to the system and with negative $D_i = -G_i$ is mitigating cost to the system.

Axiom 6 (Penalty for causing cost): From (15), if $D_i = Q_i \geq 0$, $x_i \geq 0$ *i.e.*, those individuals causing cost will pay for it.

Axiom 7 (Reward for cost mitigation): From (15), if $D_i = -G_i < 0$, $x_i < 0$ *i.e.*, those individuals mitigating cost will be rewarded. The rate of penalty and reward is same here.

And we conclude that the cost allocation defined by (15) is a cost causation based allocation. □

Theorem 3: The allocation defined by (15) satisfies standalone cost principle.

Proof: In order to prove that the cost allocation rule satisfies Axiom 5, two cases are considered.

If $D_{\mathcal{N}} \geq 0$:

$$\sum_{i\in S} x_i = \lambda D_{\mathcal{S}}, \tag{20}$$
$$C_{\mathcal{S}} = +\lambda Q_{\mathcal{S}}, \quad \text{if } D_{\mathcal{S}} \geq 0, \tag{21}$$
$$C_{\mathcal{S}} = -\mu G_{\mathcal{S}}, \quad \text{if } D_{\mathcal{S}} \leq 0. \tag{22}$$

If $D_{\mathcal{N}} \leq 0$:

$$\sum_{i\in S} x_i = \mu D_{\mathcal{S}}, \tag{23}$$
$$C_{\mathcal{S}} = +\lambda Q_{\mathcal{S}}, \quad \text{if } D_{\mathcal{S}} \geq 0, \tag{24}$$
$$C_{\mathcal{S}} = -\mu G_{\mathcal{S}}, \quad \text{if } D_{\mathcal{S}} \leq 0. \tag{25}$$

So from above, we can conclude that for every aggregation $\mathcal{S} \subseteq \mathcal{N}$:

$$\sum_{i\in S} x_i \leq C_S. \tag{26}$$

Thus the allocation satisfies standalone cost principle. □

C. Net Purchase and Sale

The cost function for a coalition $\mathcal{S} \subseteq \mathcal{N}$ and the billing time period $[t_0, t_f]$ under the net purchase and sale program is

$$C_{\mathcal{S}} = \int_{t_0}^{t_f} C_{\mathcal{S}}(t)dt, \tag{27}$$

where the instantaneous cost function $C_{\mathcal{S}}(t)$ is defined as follows:

$$C_{\mathcal{S}}(t) = \lambda Q_{\mathcal{S}}(t) - \mu G_{\mathcal{S}}(t), \tag{28}$$

where

$$Q_{\mathcal{S}}(t) = (\sum_{i\in\mathcal{S}} q_i(t) - \sum_{i\in\mathcal{S}} g_i(t))_+, \tag{29}$$
$$G_{\mathcal{S}}(t) = (\sum_{i\in\mathcal{S}} g_i(t) - \sum_{i\in\mathcal{S}} q_i(t))_+, \tag{30}$$

and the instantaneous net consumption at time t is $D_i(t) = Q_i(t) - G_i(t)$.

The net purchase and sale is equivalent to the net metering case but for each time instant $t \in [t_0, t_f]$. For this billing mechanism, the study has to be accomplished instantaneously, instead of after a billing period $[t_0, t_f]$. Consequently, the

TABLE I

CODES OF THE 80 CUSTOMERS USED IN THE STUDY

Customers Codes									
26	77	93	171	370	379	545	585	624	744
781	890	1283	1415	1697	1792	1800	2072	2094	2129
2199	2233	2557	2818	2925	2945	2980	3044	3310	3367
3456	3482	3538	3649	4154	4352	4373	4447	4767	4874
5035	5129	5218	5357	5403	5658	5738	5785	5874	5892
6061	6063	6578	7024	7030	7429	7627	7719	7793	7940
7965	7989	8046	8059	8086	8156	8243	8419	8645	8829
8995	9001	9134	9235	9248	9647	9729	9937	9971	9982

definitions and axioms of Section III are also valid, but they should be considered for each time instant $t \in [t_0, t_f]$. The results are similar and they are stated without proofs as below.

Theorem 4: The households will have successful cooperation if and only if $\lambda \geq \mu$.

Allocation 2 (Net purchase and sale): The allocated cost for the i-th household and the billing time interval $[t_0, t_f]$ is x_i, where

$$x_i = \int_{t_0}^{t_f} x_i(t)dt, \tag{31}$$

and

$$x_i(t) = \begin{cases} \lambda D_i(t), & \text{if } D_{\mathcal{N}}(t) \geq 0, \\ \mu D_i(t), & \text{if } D_{\mathcal{N}}(t) \leq 0. \end{cases} \tag{32}$$

Theorem 5: The allocation defined by (31)–(32) is a cost causation based allocation.

Theorem 6: The allocation defined by (31)–(32) satisfies standalone cost principle.

V. Case Study

We consider a community of 80 households, located in a residential area of Austin, TX, that have PV rooftop panels and decide to share their generation. The consumption and generation data have been obtained from the Pecan Street project [16]. The codes of the 80 customers, selected for this study, are given in Table I. For each customer we have retrieved real data of power consumption and solar power generation for every 15 minutes. The period under study is the complete year of 2016, and the billing period is one month. As we have analytically proved that there is no advantage of sharing under feed-in tariff, in this study, we only analyze the impact on cost and savings in sharing PV systems under net metering, and net purchase and sale.

We have considered $\lambda = ¢11.02/\mathrm{kW}$ and $\mu = 0.57\lambda$[1].

In Figure 1, we show the daily average consumption per household in black solid line. The shaded light blue area represents the interval between the 5% and 95% quantiles of the consumption distribution of the community consumers. We have chosen four specific dates in different seasons. These dates are 2016-01-01, 2016-04-01, 2016-07-01 and 2016-10-01. Since each consumer has PV rooftop panel, the daily average solar power generation per consumer is depicted in

[1] λ is the average retail price of electricity in Texas during 2016, obtained from the Energy Information Administration (EIA) Data Browser [17], and μ corresponds exclusively to the generation part of the retail price of electricity in the US according to the *Annual Energy Outlook 2017* [18].

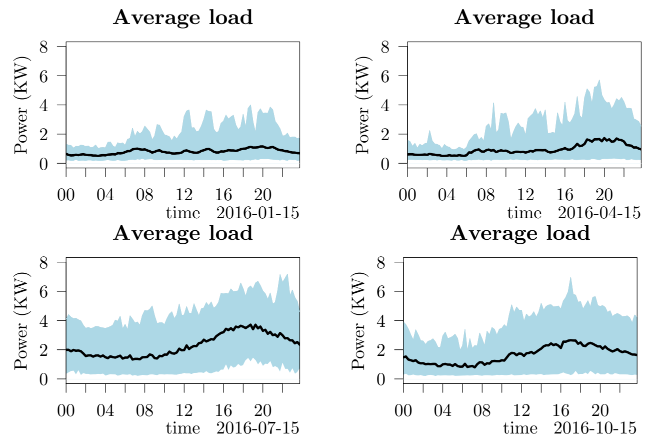

Fig. 1. Daily average load

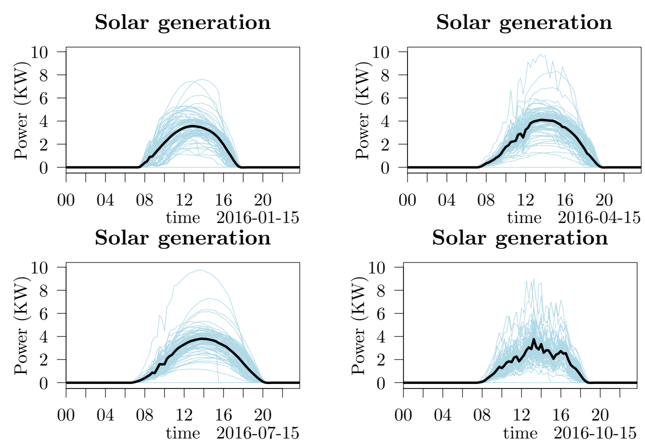

Fig. 2. Daily Solar PV generation

Figure 2 in black solid line for the same specific dates. In addition, the light blue solid lines are the power generation curves for every consumer in the community.

The total electricity consumption of the community during 2016 is $971\,681$ MW h and the total generation is $598\,349$ MW h. The monthly total consumption and generation for the 80 consumers is given in Table II. Notice that consumption is larger in summer and fall months because of the use of air conditioners. In these months the solar generation also increases but not at the same rate as that of the consumptions. The consumption increase from January to July is 236% while the generation increase is only 150%. The net consumption of the community in February and March is negative.

The average monthly consumption and generation per consumer is 1012.17 kW h and 623.28 kW h, respectively. The distribution of the monthly community consumption and generation are depicted in Figures 3 and 4, respectively. We show two plots for each figure. The first plot represents the distribution of consumption and generation per consumer, while the second one is the distribution of consumption and generation per month. The average value is represented by a solid black line with round marks. The interquantile interval between 5% and 95% is shown as a light blue bar. The remaining 10%

TABLE II
COMMUNITY MONTHLY TOTAL CONSUMPTION AND GENERATION

Month	(a)	(b)	(a)–(b)
1	56 807.87	44 503.73	12 304.14
2	48 200.62	52 105.83	−3905.21
3	52 714.26	52 944.47	−230.21
4	60 270.83	51 398.36	8872.47
5	77 184.61	48 118.61	29 066.00
6	113 583.74	61 418.20	52 165.54
7	134 202.32	66 716.79	67 485.52
8	119 990.42	54 610.72	65 379.69
9	109 313.42	54 128.38	55 185.04
10	83 020.00	53 773.55	29 246.45
11	55 200.10	33 601.74	21 598.36
12	61 193.50	25 028.61	36 164.89
Total	971 681.68	598 348.98	373 332.69

(a) Energy Consumption kW h
(b) Energy Generation kW h

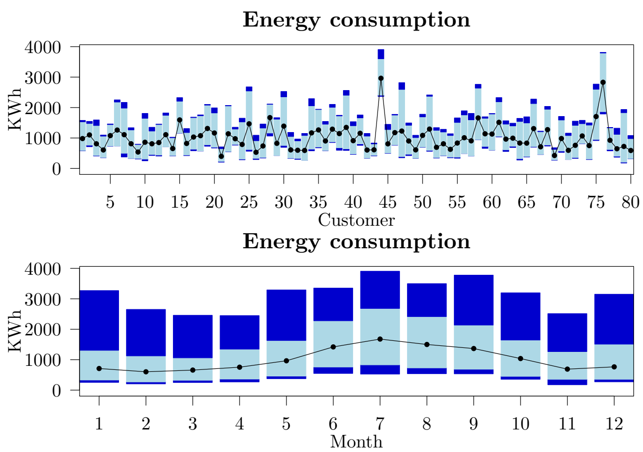

Fig. 3. Community load

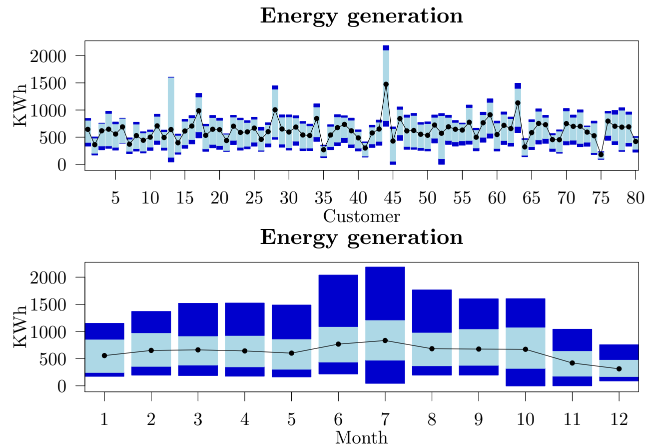

Fig. 4. Community PV solar generation

TABLE III
SUMMARY OF COST DIFFERENCES FOR NET METERING (I)

Month	(a)	(b)	(c)	(d)
1	1570.02	1355.92	−214.11	−13.64
2	136.45	−245.30	−381.75	−279.78
3	404.29	−14.46	−418.75	−103.58
4	1253.37	977.75	−275.62	−21.99
5	3289.97	3203.07	−86.90	−2.64
6	5765.62	5748.64	−16.97	−0.29
7	7444.56	7436.90	−7.66	−0.10
8	7209.74	7204.84	−4.89	−0.07
9	6106.10	6081.39	−24.71	−0.40
10	3358.26	3222.96	−135.30	−4.03
11	2445.12	2380.14	−64.98	−2.66
12	3990.26	3985.37	−4.89	−0.12
Total	42 973.74	41 337.22	−1636.52	−3.96

(a) Cost without sharing (\$), (b) Cost with sharing (\$)
(c) Cost difference (b)–(a) (\$), (d) Cost difference (c)/(a) (%)

cases are shown as dark blue bars. We can see that most residents have monthly energy consumptions near the average value with some seasonal variation. There are two residents (codes 5357 and 9647 corresponding to positions 44 and 76 in the horizontal axis) with average monthly consumptions near to 3000 kW h, much higher than the rest of residents. The plots of the rooftop PV solar generation distribution show that the monthly generation is near to the average value of 623.28 kW h with some seasonal variation. As it is expected, the generation is higher during June and July because there are more insolation hours and lower in November and December.

We analyze now the cost of energy for each resident depending on the billing mechanism[2]. In both the cases, we show a table with the sum of the costs for the 80 households for each month and a figure with the distribution of the monthly cost of electricity. We include two plots in this figure. The first plot represents the monthly cost distribution per consumer, while the second one is the customer cost per month. The average value is represented by a solid black line with round marks. The interquantile interval between 5% and 95% is shown as a light blue bar. The remaining 10% cases are shown as dark blue bars.

In Table III we show the costs for the net metering billing mechanism. In this case, the total annual cost for the community is \$42 973.74, corresponding to a monthly average per household of \$44.76. If the residents decide to share their solar rooftop generation and allocate the costs according to Allocation 1 (15), then the total annual cost is \$41 337.22 corresponding to a monthly average cost per household of \$43.10 and a cost reduction of 3.96%.

The distribution of the monthly costs and savings are depicted in Figures 5 and 6. In Figure 5 we show the monthly cost distribution, while in Figure 5 we show the monthly cost differences distribution. Note that the higher cost differences are obtained in February and March. The reason is that the net consumption in these months is negative, see Table II. Finally, in Table IV, we show the savings for the households. Due to space limitation we only show the 20 customers that obtain higher annual savings. They are ordered in decreasing order of the relative cost differences. There are 19 households that obtain a reduction higher than 10%, 30 households that obtain a reduction higher than 5% and only 7 households that do not obtain any reduction.

We conducted a similar analysis for the net purchase and

[2]Notice that we are analyzing only the cost of the consumed energy. In some European countries the cost of electricity has a term depending on the contracted power and possible penalties for exceeding the contracted power. We are not considering these terms but this does not detract from our study.

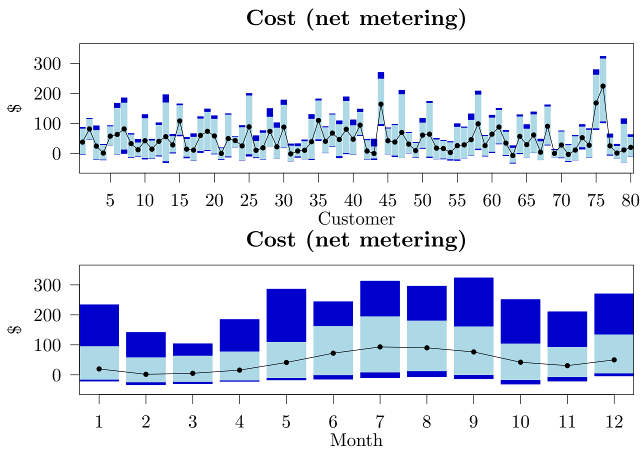

Fig. 5. Community cost for net metering billing mechanism

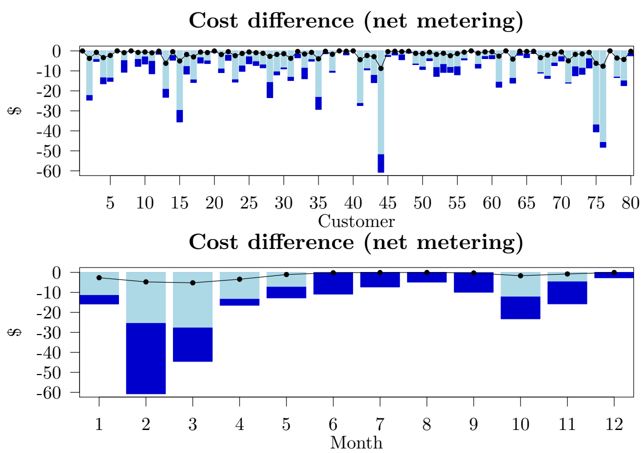

Fig. 6. Community savings for net metering billing mechanism

TABLE IV
SUMMARY OF COST DIFFERENCES FOR NET METERING (II)

Customer	(a)	(b)	(c)	(d)
5218	−3.84	−38.55	−34.71	−903.19
8645	−2.46	−20.54	−18.07	−733.38
2199	−4.48	−26.48	−22.00	−490.63
9937	10.15	−32.74	−42.90	−422.42
171	11.90	−28.52	−40.42	−339.60
3456	−20.98	−65.78	−44.81	−213.59
8995	−41.87	−101.66	−59.79	−142.80
8243	45.88	5.43	−40.45	−88.16
7024	34.27	5.24	−29.02	−84.70
8046	−86.57	−136.06	−49.50	−57.18
9971	137.10	85.52	−51.59	−37.63
5129	91.92	64.14	−27.78	−30.22
1800	129.89	93.65	−36.24	−27.90
9001	132.07	111.33	−20.73	−15.70
3538	122.99	104.27	−18.73	−15.23
5874	108.81	93.97	−14.84	−13.63
1792	168.54	146.88	−21.66	−12.85
1283	670.01	595.46	−74.55	−11.13
6063	209.11	188.03	−21.08	−10.08
2945	120.44	109.41	−11.03	−9.16

(a) Cost without sharing ($), (b) Cost with sharing ($)
(c) Cost difference (b)–(a) ($), (d) Cost difference (c)/(a) (%)

TABLE V
SUMMARY OF COST DIFFERENCES FOR NET PURCHASE AND SALE

Month	(a)	(b)	(c)	(d)
1	2773.90	1570.02	−1203.88	−43.40
2	1336.72	136.45	−1200.27	−89.79
3	1694.22	404.29	−1289.93	−76.14
4	2500.15	1253.37	−1246.78	−49.87
5	4378.49	3289.97	−1088.52	−24.86
6	6802.61	5765.62	−1036.99	−15.24
7	8442.62	7444.56	−998.06	−11.82
8	8077.89	7209.74	−868.15	−10.75
9	7071.99	6106.10	−965.89	−13.66
10	4572.32	3358.26	−1214.06	−26.55
11	3353.83	2445.12	−908.72	−27.09
12	4605.20	3990.26	−614.95	−13.35
Total	55 609.93	42 973.74	−12 636.18	−22.72

(a) Cost without sharing ($), (b) Cost with sharing ($)
(c) Cost difference (b)–(a) ($), (d) Cost difference (c)/(a) (%)

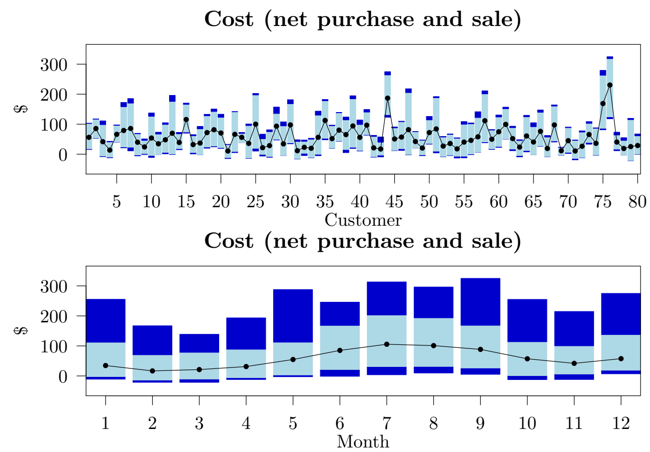

Fig. 7. Community cost for net purchase and sale billing mechanism

sale billing mechanism. In this case the cost differences by month are shown in Table III. The annual cost for the community if each household pay by her own net consumption is $55 609.93, corresponding to a monthly average per household of $57.93. If the residents decide to share their solar rooftop generation and allocate the costs according to Allocation 2 (31)–(32), then the total annual cost is $42 973.74 corresponding to a monthly average cost per household of $44.76 and a relative cost reduction of 22.72%.

The distribution of the monthly costs and savings are depicted in Figures 7 and 8. Note that in this case the cost differences are much higher than for the net metering billing mechanism. Moreover, unlike that case, the higher savings are not concentrated in two months and for a small number of customers. In Table VI, we show the savings for the households. Similarly to the net metering case, we only show the 20 customers that obtain higher annual savings and they are ordered in decreasing order of the relative cost differences. Every household obtains a significant reduction of her energy cost. There are 21 households that obtain a reduction higher than 50%, 52 households obtain a reduction higher than 20%, 70 higher than 10% and only one has a reduction lower than 1%.

We conclude this section by remarking that net metering

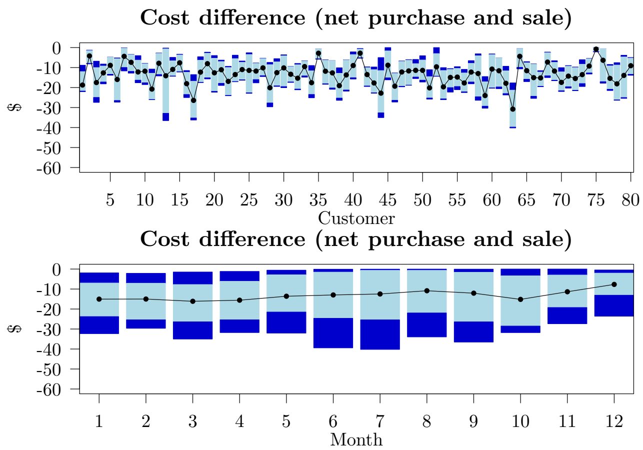

Fig. 8. Community savings for net purchase and sale billing mechanism

TABLE VI
SUMMARY OF COST DIFFERENCES FOR NET PURCHASE AND SALE (II)

Customer	(a)	(b)	(c)	(d)
8995	129.49	−41.87	−171.37	−132.34
8046	282.91	−86.57	−369.47	−130.60
3456	139.16	−20.98	−160.14	−115.07
2199	128.52	−4.48	−133.00	−103.49
5218	208.66	−3.84	−212.50	−101.84
8645	138.64	−2.46	−141.11	−101.78
9937	227.65	10.15	−217.50	−95.54
171	163.75	11.90	−151.85	−92.73
7024	213.38	34.27	−179.12	−83.94
8243	228.18	45.88	−182.30	−79.89
1800	446.96	129.89	−317.07	−70.94
3482	276.09	92.10	−183.99	−66.64
5129	253.90	91.92	−161.98	−63.80
781	416.68	167.39	−249.29	−59.83
9001	317.79	132.07	−185.72	−58.44
1792	385.18	168.54	−216.64	−56.24
5874	245.45	108.81	−136.64	−55.67
9971	304.19	137.10	−167.08	−54.93
6578	429.52	193.67	−235.85	−54.91
2945	261.49	120.44	−141.05	−53.94

(a) Cost without sharing ($), (b) Cost with sharing ($)
(c) Cost difference (b)–(a) ($), (d) Cost difference (c)/(a) (%)

produces lower costs for the households than net purchase and sale. But from the point of view of saving cost due to sharing, net purchase and sale is the most interesting as it promotes association by an effective sharing of the energy excesses and producing significant reduction of the energy costs for every household.

VI. CONCLUSIONS

Drastic cost reduction in the PV systems technology in the last few years has resulted in significant increase in their worldwide installation. Attractive billing methods implemented by different system operators has also encouraged more houses to install PV systems. In this paper, we have explored the idea of sharing the electricity generation by PV systems of different households among each other and improving their profits promoting the use of clean energy more in the power system. We have considered sharing under three different programs: feed-in tariff, net metering, and net purchase and sale. In feed-in tariff, there is no advantage in sharing. In net metering, and net purchase and sale, sharing is advantageous if and only if the retail price of electricity by the utility is more than the price of selling electricity to the utility. Under that favorable sharing condition, we found rules for allocating their joint cost based on cost causation principle. The allocations also follow standalone cost principle, *i.e.*, they are in the core of the cooperative games of net electricity consumption cost. These results will definitely attract more households to share their PV systems generated electricity with each other and as a result, the whole society will be benefited. We have verified our developed results in the data set of a community of residential households in Austin, Texas.

REFERENCES

[1] G. L. Barbose and N. R. Darghouth, “Tracking the sun ix: The installed price of residential and non-residential photovoltaic systems in the united states,” 2016.

[2] J. E. Hughes and M. Podolefsky, “Getting green with solar subsidies: evidence from the california solar initiative,” *Journal of the Association of Environmental and Resource Economists*, vol. 2, no. 2, pp. 235–275, 2015.

[3] S. A. Kalogirou, “Environmental benefits of domestic solar energy systems,” *Energy conversion and management*, vol. 45, no. 18, pp. 3075–3092, 2004.

[4] “Renewables 2017-global status report,” *Renewable Energy Policy Network for the 21st Century*, 2017.

[5] Y. Yamamoto, “Pricing electricity from residential photovoltaic systems: A comparison of feed-in tariffs, net metering, and net purchase and sale,” *Solar Energy*, vol. 86, no. 9, pp. 2678–2685, 2012.

[6] J. Warrick, “Utilities wage campaign against rooftop solar,” *Washington Post*, vol. 7, 2015.

[7] H. Heinrichs, “Sharing economy: a potential new pathway to sustainability,” *Gaia*, vol. 22, no. 4, p. 228, 2013.

[8] G. Zervas, D. Proserpio, and J. W. Byers, “The rise of the sharing economy: Estimating the impact of airbnb on the hotel industry,” *Journal of Marketing Research*, 2014.

[9] E. Baeyens, E. Y. Bitar, P. P. Khargonekar, and K. Poolla, “Coalitional aggregation of wind power,” *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 3774–3784, 2013.

[10] P. Chakraborty, E. Baeyens, and P. P. Khargonekar, “Cost causation based allocations of costs for market integration of renewable energy,” *IEEE Transactions on Power Systems*, vol. PP, no. 99, pp. 1–1, 2017.

[11] H. Nguyen and L. Le, “Bi-objective based cost allocation for cooperative demand-side resource aggregators,” *IEEE Transactions on Smart Grid*, 2017.

[12] C. Wu, D. Kalathil, K. Poolla, and P. Varaiya, “Sharing electricity storage,” in *Decision and Control (CDC), 2016 IEEE 55th Conference on*. IEEE, 2016, pp. 813–820.

[13] P. Chakraborty, E. Baeyens, P. P. Khargonekar, and K. Poolla, “A cooperative game for the realized profit of an aggregation of renewable energy producers,” in *2016 IEEE 55th Conference on Decision and Control (CDC)*, Dec 2016, pp. 5805–5812.

[14] B. Kirby, M. Milligan, and Y. Wan, “Cost-causation-based tariffs for wind ancillary service impacts,” in *Windpower*, 2006.

[15] Edison Electric Institute, “Straight Talk About Net Metering,” January 2016.

[16] Pecan St. Project. [Online]. Available: http://www.pecanstreet.org/

[17] U.S. Energy Information Administration: Data Browser. [Online]. Available: https://www.eia.gov/electricity/data/browser/

[18] U.S. Energy Information Administration, “Annual energy outlook 2017,” January 2017.