Solar Energy 140 (2016) 188–198

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

The microeconomics of residential photovoltaics: Tariffs, network operation and maintenance, and ancillary services in distribution-level electricity markets

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A R T I C L E   I N F O

Article history:
Received 14 July 2015
Received in revised form 25 October 2016
Accepted 3 November 2016
Available online 12 November 2016

Keywords:
Residential photovoltaics
Ancillary services
Feed-in tariffs
Net metering

A B S T R A C T

We develop a microeconomic model of a distribution-level electricity market that takes explicit account of residential photovoltaics (PV) adoption. The model allows us to study the consequences of most tariffs on PV adoption and the consequences of increased residential PV adoption under the assumption of economic sustainability for electric utilities. We validate the model using U.S. data and extend it to consider different pricing schemes for operation and maintenance costs of the distribution network and for ancillary services. Results show that net metering promotes more environmental benefits and social welfare than other tariffs. However, if costs to operate the distribution network increase, net metering will amplify the unequal distribution of surplus among households. In conclusion, maintaining the economic sustainability of electric utilities under net metering may become extremely difficult unless the uneven distribution of surplus is legitimated by environmental benefits.

1. Introduction

Recent reductions in the total cost of installing residential photovoltaic (PV) systems have increased global diffusion (Rigter and Vidican, 2010; Thiam, 2011; Lin and Wesseh, 2013; Chowdhury et al., 2014) of this renewable energy source. Changes in technology and markets have reduced both PV module production costs (Goodrich et al., 2012) and installation costs (Friedman et al., 2013). Further, public policies (Timilsina et al., 2012; Dong et al., 2014; Jimenez et al., 2016) in the form of rebates (Kwan, 2012) or tax credits (Burns and Kang, 2012) have encouraged an increasing number of households to adopt PV systems.

There are concerns that high rates of residential PV adoption may impact electricity distribution networks. In particular, it has been noted that the diffusion of residential PV requires new and updated grid equipment (Eltawil and Zhao, 2010), and that it reduces utility revenues more than it reduces costs. These considerations introduce additional economic and financial challenges (Satchwell et al., 2014) for utilities. There are additional concerns that public polices *vis a vis* utility budget constraints can cause costs to be shifted between households.

These issues and others suggest the need for a better understanding of how different tariff mechanisms affect PV adoption rates, social welfare, and the surplus distribution between households.

Case studies so far have pointed out how policies (Burns and Kang, 2012; Chowdhury et al., 2014), social dynamics (Guo and Song, 2015), and economic incentives (Rigter and Vidican, 2010; Jimenez et al., 2016) contribute to PV adoption and to its emerging patterns (Guidolin and Mortarino, 2010; Kwan, 2012). Along empirical studies, models of innovation diffusion (Rao and Kishore, 2010; Popp et al., 2011; Hsu, 2012; Islam, 2014) have focused on processes of technology adoption.

The analytical concerns mentioned above require a different modeling approach capable of concurrently representing the dispersed and individual-level decision-making typical of PV diffusion (Islam, 2014; Guo and Song, 2015), the system-level effects impacting the environment, households, social welfare, and electric utilities through tariffs and costs, and the complex feedback between those levels.

We develop a microeconomic model of a distribution-level electricity market that extends the model presented in Yamamoto (2012). The model presented in this paper addresses household

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Abbreviations: APS, Arizona Public Service; EIA, U.S. Energy Information Administration; FIT, feed-in tariff; JCP&L, Jersey Central Power & Light; NetM, net metering tariff; NetPS, net purchase and sale tariff; O&M, operation and maintenance; PG&E, Pacific Gas & Electric; PSE&G, Public Service Electric and Gas Company; SRP, Salt River Project; SCE, Southern California Edison; SDG&E, San Diego Gas & Electric; TEP, Tucson Electric Power.

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http://dx.doi.org/10.1016/j.solener.2016.11.010

investment in PV and incorporates budget constraints on electric utilities. Incorporating utility budget constraints allows us to examine issues relating to how pricing mechanisms affect household incentives to adopt PV and how household PV penetration rates affect distribution utility profitability. This approach also allows us to examine how electricity surpluses are distributed between households. Finally, this approach also allows comparing the effects of different tariffs (Lesser and Su, 2008; Cory et al., 2009) on both household surplus and social welfare (Wand and Leuthold, 2011).

After presenting the validation of the basic theoretical model using data observed in the United States under the net metering tariff, we extend it to investigate the challenges posed by increasing and additional costs due to PV adoption. We study the interaction between tariffs and schemes implemented to collect resources for the most common additional costs introduced by PV, which are for operating and maintaining the distribution network and ancillary services.

We conclude with a brief discussion of the main results and limitations of our analysis and sketch possible future directions of research.

2. The basic model

We consider the presence of a finite number of households N. Each household installs residential PV if the investment is profitable. Households adopting residential PV determine the supply of PV-generated energy. Further, an electric utility EU sells electricity, provides the distribution network, buys PV-generated electricity, and buys electricity and ancillary services from utility-scale conventional and renewable energy generators. Households are consumers, but become producers if they install solar panels. The electric utility is an intermediary, selling electricity generated at the utility scale to all households and buying and selling power from PV-adopting households. The electric utility is also a service provider (distribution network maintenance, reliable and secure power flow, etc.).

Exchanges between the electric utility and utility-scale power generators happen at a wholesale spot price c, which is determined by dynamics in the electricity market at the transmission level. Exchanges of power between the electric utility and households happen according to two regulated prices. The first, r, is the standard retail rate at which the household would purchase power from the utility. The second, p, is the price paid by the utility when buying residential PV energy from the household.

2.1. Tariffs

We consider here three tariffs commonly found in contemporary electricity markets. The first one is *net metering* (NetM). It is based on the household-level compensation of generation and consumption over a rather long billing period, typically lasting between one month and one year. Under NetM, at the end of the billing period the accounting balance between consumption and generation is computed. If the household has generated more than it has consumed in the period, it sells the difference to the electric utility at price p. Otherwise, the household buys the excess of consumption from the electric utility at price r.

The second tariff is *net purchase and sale* (NetPS). It is similar to net metering in that it is determined partly by the net difference consumed and generated. Under NetPS, the compensation is computed continuously using the shortest possible billing interval, typically every 15 min. Moreover, NetM would converge to NetPS if the billing period were to be shortened as much as possible.

The third tariff we consider is the *feed-in tariff* (FIT). This tariff is based on readings from two separated household meters in households that have installed PV. One meter measures electricity consumption while the other measures electricity generation. Under FIT, the whole generation is sold to the electric utility at price p and the whole consumption is paid by households at price r.

Finally, if z_i is the amount of electricity household i generates with solar panels, we can use the parameter t to model the billing effect of different tariffs. Specifically, $(t)z_i$ indicates the amount of PV-generated energy sold by household i to the electric utility, and $(1-t)z_i$ represents the part of z_i that is used to offset household consumption.

Let q_i represent the quantity of electricity consumed by household i. In Duke et al. (2005), empirical evidence suggests that the average generating power of residential solar panels is strictly lower than household needs ($\sum_N z_i < \sum_N q_i$). We assume this holds at the consumer level as well, $z_i < q_i$. Under FIT, $t = 1$, and all PV-generated electricity is sold to the electric utility and none is used to offset consumption because generation and consumption are metered separately. Under NetPS, $0 < t < 0.5$ because $z_i < q_i$. Under NetM, we have $0 < t < 0.5$ as well, but in this case t will be lower than in NetPS because the billing period is longer. Table 1 summarizes the values of the t under each tariff scheme.

2.2. Residential PV supply function

We assume that household demand for electricity is a constant q_i, is exogenous, and is inelastic.

2.2.1. Household investment decision

The household investment decision in PV is a simple binary decision, with investment occurring if household utility derived from investing exceeds household utility from not investing.

Eq. (1) shows the household utility function u_i for the investment in PV, where K_i is the discounted cost of installing, operating, and maintaining solar panels for their expected lifetime,

$$u_i = -K_i + p(t)z_i + r(1-t)z_i. \tag{1}$$

Under FIT, r does not influence household utility because generated electricity is sold entirely to the electric utility at price p and no generated electricity is used to reduce demand q_i.

2.2.2. Derivation of the supply function

From Eq. (1) we know that each household has a reservation price p_i, below which household investments in PV are not profitable,

$$p_i = \frac{k_i - r(1-t)z_i}{t_i z_i} = \frac{1}{t}\left(\frac{k_i}{z_i} - r(1-t)\right). \tag{2}$$

If we order the households from 1 to N according to an increasing reservation price, we obtain the supply function in Fig. 1.

Further, defining Z as the sum of energy generated by households with residential PV ($Z = \sum_N z_i$) and k as the average total cost of a unit of residential PV generation capacity $\left(k = \frac{\sum_N k_i}{\sum_N z_i}\right)$, we can linearize the supply function,

$$p = \frac{1}{t}(k - r(1-t))Z. \tag{3}$$

Table 1
Definition of tariff parameters.

Tariff	Acronym	Parameter Value
Net metering	NetM	$0 < t_{NetM} < t_{NetPS}$
Net purchase and sale	NetPS	$0 < t_{NetPS} < 0.5$
Feed-in tariff	FIT	$t_{FIT} = 1$