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Implications of high-penetration renewables for ratepayers and utilities in the residential solar photovoltaic (PV) market

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HIGHLIGHTS

- Optimal solar array size (lowest LCOE) reduces by 20–50% if net metering is removed.
- Batteries are cost-effective without net metering and a price decrease of at least 55%.
- Simulations show "duck curve" behavior for 10,000 homes at various solar PV levels.
- Energy use (kW h) reduces by an equivalent percent increase in solar PV penetration.
- Utility revenue recovery models are evaluated through increased rates and fees.

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ABSTRACT

Residential energy markets in the United States are undergoing rapid change with increasing amounts of solar photovoltaic (PV) systems installed each year. This study examines the combined effect of electric rate structures and local environmental forcings on optimal solar home system size, ratepayer financials, utility financials, and electric grid ramp rate requirements for three urban regions in the United States. Techno-economic analyses are completed for Chicago, Phoenix, and Seattle and the results contrasted to provide both generalizable findings and site-specific findings. Various net metering scenarios and time-of-use rate schedules are investigated to evaluate the optimal solar PV capacity and battery storage in a typical residential home for each locality. The net residential load profile is created for a single home using BEopt and then scaled to assess technical and economic impacts to the utility for a market segment of 10,000 homes modeled in HOMER. Emphasis is given to intraday load profiles, ramp rate requirements, peak capacity requirements, load factor, revenue loss, and revenue recuperation as a function of the number of ratepayers with solar PV. Increases in solar PV penetration reduced the annual system load factor by an equivalent percentage yet had little to no impact on peak power requirements. Ramp rate requirements were largest for Chicago in October, Phoenix in July, and Seattle in January. Net metering on a monthly or annual basis had a negligible impact on optimal solar PV capacity, yet optimal solar PV capacity reduced by 20–50% if net metering was removed altogether. Technical and economic data are generated from simulations with solar penetration up to 100% of homes. For the scenario with 20% homes using solar PV, the utility would need a 16%, 24%, and 8% increase in time-of-use electricity rates ($/kW h) across all ratepayers to recover lost revenue in Chicago, Phoenix, and Seattle, respectively. The $15 monthly connection fee would need to increase by 94%, 228%, or 50% across the same cities if time-of-use electricity rates were to remain unchanged. Batteries were found to be cost-effective in simulations without net metering and at cost reductions of at least 55%. Batteries were not cost-effective—even if they were free—when net metering was in effect. As expected, Phoenix had the most favorable economic scenario for residential solar PV, primarily due to the high solar insolation.

1. Introduction

Addressing the societal demand for low-carbon energy is an ongoing challenge that will persist for several decades. It has been suggested that a zero-carbon economy can be realized in the United States by 2050 through changes in technology, policy, eco-

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nomics, business models, and consumer behavior [1]. Yet that year is far away, and much progress is needed. For now, the increasing amount of research and practice in reducing carbon emissions hint that a zero-carbon future may be possible [2–4].

The long-term vision for carbon-free energy has been pursued with research in renewables design and integration [5,6], grid stability at high levels of renewable penetration [7–11], building energy systems design and analysis [12–14], energy efficiency in end-use devices [15–17], thermal energy storage to offset air conditioning loads [18,19], and studies of the social, political, and economic implications of transitioning to a low-carbon future [20–24]. The diversity of topics covered in the literature is an indication of the complexity and the challenges faced when integrating distributed energy resources (DER) from the individual circuit to the larger grid.

Household solar photovoltaic (PV) systems have become increasingly common in the United States, with a current annual growth rate of 58% [25]. Solar home systems commonly produce excess electricity during the daytime to displace grid purchases during off-sun hours. This excess electricity can be stored in batteries for later use, or credited to the customer through a feed-in tariff or net metering. Net metering is a billing agreement that allows customers to use the credited electricity at another time when solar PV generation is less than the household load. Net metering is a major factor in solar PV adoption [26]. The ability to use the grid as a "zero cost lossless battery" is unquestionably an economic advantage for the consumer (ratepayer). A feed-in tariff is another form of billing agreement [27]. In a feed-in tariff billing agreement, the ratepayer is compensated monetarily for excess production, whereas in net metering the ratepayer receives kilowatt-hour energy credits by "rolling back the meter" during periods of excess production.

The technical and economic implications of small amounts of household solar PV are minimal to the utility, but at higher penetration levels, solar PV is expected to cause grid instability and disrupt utility business models [28]. A primary concern is managing the significant rise in electrical demand that occurs during the late afternoon when solar output declines and residential loads increase as people arrive home from work or school. This increases the ramp rate requirement from dispatchable generation as popularized in the "duck curve" or "duck chart" [29]. Intermittency in renewables is another point of concern when noting that utilities must keep sufficient reserves (e.g., dispatchable generation, storage, and demand response) online to displace potential disruptions in solar PV power output caused by clouding or other effects [28,30]. These issues may become more prevalent over time as distributed solar PV capacity continues to increase.

2. Background

A growing body of research has explored the technical and economic implications of high-penetration distributed residential solar PV [31,26,32–37]. It is clear that the declining costs of solar modules have contributed to increases in the installed capacity of solar PV (EA 2008). Total hardware costs have dropped from $3.30 per watt to $1.83 per watt between 2010 and 2012, with current module prices at under $1.00 per watt [38,39]. Recent work is seeking to reduce costs further by targeting the "soft costs" of solar installation such as labor, supply chain, permitting, and transaction costs. Soft costs comprised approximately two-thirds of the total installed cost of $5.22 per watt in 2012 [38]. Additional reductions in cost to the end-user were available through tax incentives, subsidies, and rebates offered by governments and utilities [40,37]. Leasing is also an attractive option that offers a no-money-down solution with low financing charges. Current systems can be leased on 20-year or 25-year agreements for as little as $3.00 per watt to the end-user after accounting for rebates, incentives, financing charges, and maintenance and warranty costs [41,33,42].

The economic advantage of home solar is not universal for all ratepayers. An analysis of local electric rate structures must be performed to determine if solar PV reduces the levelized cost of electricity (LCOE) for the end-user vis-à-vis grid power alone [31,34]. Areas with higher costs of electricity and favorable distributed generation policies—such as Hawaii (USA), Germany, and Denmark—have experienced substantial increases in solar PV penetration whereas regions with lower electricity costs and more strict owner-side generation policies—such as fossil-fuel rich industrialized economies—have seen solar PV penetration grow at a slower rate [43–45]. Net metering has been suggested as one of the leading contributors to the growth of the residential solar PV market [26]. Feed-in tariffs have also contributed to solar PV adoption and often begin with a high feed-in tariff to spur the installation of solar and then reduce the tariff's value over time as a way to slow down the rate of solar PV adoption [34,46,47].

Electric utility business models will not be insolated from the rise in distributed solar PV. Instead, it has been surmised that solar PV consumers will have the strongest effect on utility revenue [36]. According to a scoping study conducted by Lawrence Berkeley National Laboratory, a solar PV penetration rate reducing 10% of retail sales at a Northeast wires-only distribution utility was found to reduce the return on equity by 40% with a corresponding 15% reduction in achieved earnings and an average rate increase of 2.7% for ratepayers [48]. This suggests that the loss of revenue from solar PV customers could be recouped through rate increases for all customers—solar and non-solar homes.

Aside from revenue loss, uncontrolled renewables can create over-production issues within a region when thermal base-loading power plants need to operate at a minimum load or provide reserve capacity [47]. In addition, fluctuations in solar PV output can cause disturbances in voltage and frequency that fatigue hardware and reduce equipment lifetime [49–52]. Further studies are needed to explore these and other challenges of high-penetration solar PV integration [32]. Yet for now, it can be surmised that the unfolding of the residential solar PV market will not continue business as usual for utilities, customers, and technology providers. Modeling approaches and stakeholder engagement efforts that represent, contrast, and integrate the perspectives of various parties can facilitate energy planning decisions for mutual gain [53,54].

This article contrasts the objectives of residential ratepayers and an electric utility by simulating the combined effect of electric rate structures and local environmental forcings on optimal home energy system size, ratepayer financials, and utility technical and financial factors. Analyses are completed of three urban cities (Chicago, Phoenix, and Seattle) in the United States and then contrasted to provide both generalizable findings and site-specific findings. Various time-of-use pricing schedules are investigated, and the effect of net metering is evaluated to determine the optimal capacity of solar PV and battery storage in a typical residential home. The residential load profile is scaled to assess system-wide technical and economic merits of interest to a utility at low-, medium-, and high-penetration solar PV scenarios.

3. Methodological approach

A variety of models are available for evaluating changes in the residential solar PV market. These include elements of expansion planning for modeling system-wide effects of load growth and generation assets, and production cost modeling and economic dispatch for dispatching energy sources to deliver the least cost