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On the utility death spiral and the impact of utility rate structures on the adoption of residential solar photovoltaics and energy storage

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HIGHLIGHTS

- A death spiral occurs only with both high PV adoption rates and high utility costs.
- Community solar and rental property PV adoption increase risk of a death spiral.
- The net metering pricing structure both rewards DG and reduces grid defection.
- Our novel system dynamics model is available open-source for the research community.

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ABSTRACT

Today, many electric utilities are changing their pricing structures to address the rapidly-growing market for residential photovoltaic (PV) and electricity storage technologies. Little is known about how the new utility pricing structures will affect the adoption rates of these technologies, as well as the ability of utilities to prevent widespread grid defection. We present a system dynamics model that predicts the retail price of electricity and the adoption rates of residential solar photovoltaic and energy storage systems. Simulations are run from the present day to the year 2050 using three different utility business models: net metering, wholesale compensation, and demand charge. Validation results, initialized with historical data for three different cities, agree well with expert forecasts for the retail price of electricity. Sensitivity analyses are conducted to investigate the likelihood of a "utility death spiral", which is a catastrophic loss of business due to widespread grid-defection. Results indicate that a utility death spiral requires a perfect storm of high intrinsic adoption rates, rising utility costs, and favorable customer financials. Interestingly, the model indicates that pricing structures that reduce distributed generation compensation support grid defection, whereas pricing structures that reward distributed generation (such as net metering) also reduce grid defection and the risk of a death spiral.

1. Introduction

The 'utility death spiral' is a positive feedback loop, in which electric utility customers switch to distributed-generation and/or make efficiency improvements, causing a steep decline in electricity demand, in turn causing increased retail electric prices, driving more customers to reduce their demand, and so on until the utility becomes an unsustainable business. The first threat of a death spiral arose after the 1973 Arab Oil Embargo, when rising fuel prices and efficiency measures cut into utility profits [1]. However, these fears were found to be based on unrealistic conditions, and the conclusion was that if utilities, customers, and regulators behaved rationally, the death spiral would not happen [2].

Recently, concern of a utility death spiral has found new legs, because of the growing adoption of distributed energy generation systems, especially solar photovoltaics (PV) [3–6]. Solar PV is growing faster than any other distributed generation (DG) technology [7], and installed PV costs are dropping rapidly [8–10]. Furthermore, financial incentives such as net-metering make distributed generation (DG) systems more attractive to consumers while simultaneously reducing utility revenues [11,12]. Additionally, utility fixed costs are rising due to several factors: modernizing measures such as smart-grid technologies, maintenance of aging transmission and distribution infrastructure, environmental regulations, and rising costs of fossil fuels [8,13]. These factors combine to raise volume-based prices, which in turn encourage more customers to adopt DG systems and reduce their demand to save money. If these trends continue, US utilities could lose from $18 to $48 billion per year over the next decade [14].

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Nomenclature

DG	Distributed Generation (n/a)
PV	Photovoltaic (n/a)
ELCC	Effective Load Carrying Capability (n/a)
FCI	Fixed Capital Investment ($)
NPV	Net Present Value ($)
RoR	Required Rate of Return (unitless)
$F(t)$	installed base fraction (unitless)
$f(t)$	rate of change of the installed base fraction (time^{-1})
p	coefficient of innovation (unitless)
q	coefficient of imitation (unitless)
C_v	variable cost ($)
C_f	fixed cost ($)
D	cumulative electricity demand (kW h)
L	limit function for homes with PV systems (unitless)
N_{reg}	number of regular households (homes)
N_{PV}	number of PV households (homes)
N_{def}	number of defected households (homes)
d	drain-slowing function (unitless)
h	households adopting a technology per unit time (homes/time)
k	innovation/imitation rate scaling factor (unitless)
R	adoption rate (Note: h, k, and R use the following 6 subscripts to distinguish between the 6 adoption pathways) (% homes/time)
PN	photovoltaic innovation (n/a)
PM	photovoltaic imitation (n/a)
BN	battery innovation (n/a)
BM	battery imitation (n/a)
DN	direct defection innovation (n/a)
DM	direct defection imitation (n/a)

Today, a new threat to the traditional utility business model is emerging: energy storage combined with affordable PV systems raises the prospect of consumer grid defection [8]. Battery technology is an extremely active field of research (for example [15–17]) and battery prices are expected to drop significantly in the near future [8,18]. Combined, PV and battery systems could create disruptive competition for utilities [4].

Of course, other businesses in the energy supply chain are likely to be affected as the residential PV market share increases. For example, many utility-scale generation plants, including coal and natural gas generators as well as wind farms, will see a decrease in demand [19]. However, recent work by Cole et al. [20] indicates that distributed PV systems may be competing only with utility-scale PV systems.

While there is disagreement on the root cause of a potential death spiral, there is a consensus that utilities must adapt [21,11,4,22,1]. Raskin [11] argues that by the time DG is a real threat to utilities, a solution will have been found via the "regulatory compact": an unspoken relationship between utilities and regulators that allows utilities to attract investments that are necessary to maintain reliable service and meet regulatory requirements. Many agree, including Raskin, that net-metering is an unfair and unsustainable subsidy for DG systems that will not be allowed to persist, which will reduce the risk of a death spiral [1,22]. Graffy and Kihm [4] argue that protecting utilities through regulation might not be able to sustain utilities through the disruptive competition created by a myriad of factors, including improving DG technologies, expanding renewable portfolio standards, morphing consumer preferences and practices, and innovative businesses providing more attractive options than utilities currently offer. Felder and Athawale [1] suggest that a death spiral will not be the result of disruptive competition, but rather rate design. They argue that the current volumetric rate design, which spreads the utility's cost equally across most customers, is not viable for recovering utility fixed costs.

Few groups have attempted to model the complex interactions between the adoption of PV and storage systems, utility costs, and retail rate design. To the authors' knowledge, our model is the first to capture these complex feedback loops, as well as the potential for grid defection. Darghouth et al. [23] found that PV adoption rates are very sensitive to utility rate structures. Their results indicate that if utilities employ time-of-use rates they can offset the economic losses from net-metering pricing structures, thus damping the positive feedback loop between escalating retail prices and the number of distributed PV systems. However, Darghouth et al. did not include the option for utility customers to use batteries to flatten their demand curve and therefore take advantage of time-of-use rates or defect from the grid. Satchwell et al. [24] modeled the effects of increasing PV adoption on the profitability of electric utilities and the retail price of electricity; they found that as the PV adoption level increases, the utilities' costs increase faster than revenues, leading to greater average retail prices and reduced utility profits. Sigrin et al. [25] (of the U.S. National Renewable Energy Laboratory) are currently adding a storage adoption model to their existing dGen model, which forecasts the adoption of distributed energy resources for residential, commercial, and industrial customers in the U.S.

1.1. Scope of this article

This article presents a novel system dynamics model that captures the feedback loops required for a utility death spiral, namely the nonlinear interactions between utility costs, utility business model, the retail price of electricity, adoption rates of solar photovoltaics and energy storage technologies, and grid defection. Prior models have attempted to predict distributed generation (DG) adoption rates using fixed retail price forecasts, which do not take into account the impact that greater market penetration of DG technologies has on the electricity retail price. Our electricity retail price model captures the complex, nonlinear feedback between the electricity retail price and the number of homes with and without PV systems, as well many other market factors. Our model is implemented in Stella and is available open-source, in order to provide a platform for industry, policy makers, and researchers to rapidly evaluate the effects of different technologies, utility pricing structures, and government incentives on the impacts of integrating distributed-generation systems into the residential electric grid.

This article presents the modeling methodology as well as three case studies. We simulate the effects of residential PV and storage adoption on the retail price of electricity, and vice versa, out to 2050. As three example cases, we simulate residential Los Angeles, California; Sydney, Australia; and Boulder, Colorado. For each of these three locations, three different utility business models (i.e. pricing structures for the compensation of DG customers) are compared.

Los Angeles (LA) was chosen for this study for a combination of reasons: high retail prices (currently $\approx 40\%$ greater than the national average [10,8]), high solar potential [26], and the rapidly growing number of installed solar photovoltaic (PV) (see Fig. 1). Similar to LA, Sydney has seen rapid growth in residential PV systems in recent years and represents a large metropolis with high