Residential Distributed Generation Systems and the Traditional Utility Business Model: Is a Utility Death Spiral a Viable Threat?

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Abstract

The unknown costs of integrating rapidly growing distributed generation systems (DG) into an aging grid have once again thrust the idea of a utility death spiral into the limelight. Using system dynamics modeling, we simulate a traditional regulated utility business model in Los Angeles, California, Sydney, Australia, and Boulder, Colorado. The model forecasts the residential electricity retail rate and investigates the impacts of declining photovoltaic (PV) and battery systems prices on a utility's ability to retain customers and therefore remain a viable business. Three types of utility business models are investigated: net metering, demand charge, and compensating DG customers with a rate less than retail.

Our model indicates that a utility death spiral due to customers shifting from conventional electricity providers to distributed PV and off-grid PV is highly unlikely. A death spiral was indicated to occur only with combinations of extremely high values of adoption rates, consumer incentives, growth in utility costs, and nearly zero required rates of return by customers using a net present value criteria.

1 Background

A utility death spiral - in which customers switch to distributed technologies and/or efficiency improvements cause a steep decline in demand for power from traditional utilities - is not a new concept. After the oil embargo of 1973, rising fuel prices and efficiency measures cut into utility profits and raised fears of a death spiral [1]. However, these fears were found to be based on "unrealistic conditions" for the three primary stakeholders: utility managers' reaction to financial loss; customers' response to higher retail prices; and regulators' willingness to protect utilities [2].

More recently, concern over the possibility of a utility death spiral has found new legs in the growing adoption of grid-connected distributed generation systems, especially solar photovoltaics (PV) [3, 4, 5]. Solar PV is growing faster than any other energy generation technology [6]. Though PV systems have not yet reached price parity with grid supplied electricity, installed PV costs are dropping rapidly [7]. For example, in June, 2015 the average retail price of electricity in Los Angeles County was \$0.21/kWh [8] (the national average was \$0.13/kWh [9]), and the levelized cost of electricity from a 5kW PV system was approximately \$0.30/kWh (see Appendix B). Furthermore, financial incentives such as net-metering make distributed generation (DG) systems more attractive to consumers while simultaneously reducing utility revenues [10]. Additionally, utility fixed costs are rising due to modernizing measures (such as smart-grid technologies), maintenance of aging transmission and distribution infrastructure, environmental regulations, and rising costs of fossil fuels [7, 11]. 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 utilities in the US could lose from \$18 billion to \$48 billion per year over the next decade [12].

Today, a new threat to the traditional utility business model is emerging: energy storage combined with distributed generation raises the prospect of consumer grid defection [7]. Battery technology is an extremely active field of research (for example [13, 14, 15, 16]) and battery prices are expected to drop significantly in the near future [7, 17]. Combined, PV and battery systems could create disruptive competition for utilities [4].

While there is disagreement on the root cause of a potential death spiral, there is a consensus that utilities must adapt [18, 10, 4, 19, 1]. Raskin 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 [10]. 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, 19]. Graffy and Kihm 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 [4]. Felder and Athawale state 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 (some large energy consumers may receive special negotiated rates), is not viable for recovering utility costs [1].

There is no doubt that utilities and regulators face a changing tide of consumers reducing electricity use and a growing public sentiment for reducing greenhouse gas emissions. If battery technology has a breakthrough that drastically drops costs and raises storage capacity before utilities are able to adapt then utilities in areas with high solar energy will certainly be faced with an existential crisis.

2 Scope

We view the utility death spiral as a positive feedback loop between rising retail prices and residential DG system adoption. The work outlined here simulates the traditional utility business model and forecasts the effects of residential DG 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 the three locations, three different pricing structures for the compensation of DG customers are compared. Our goal in creating this model was to determine what sort of scenarios could create a utility death spiral and in doing so determine if a death spiral is a real threat to utilities.

Los Angeles (LA) was chosen for this study for a combination of reasons. High retail prices (currently $\approx 40\%$ greater than the national average [9, 7], high solar potential [20], and the rapidly growing number of installed solar photovoltaic (PV) (Figure 1) make LA a likely candidate for the death spiral.

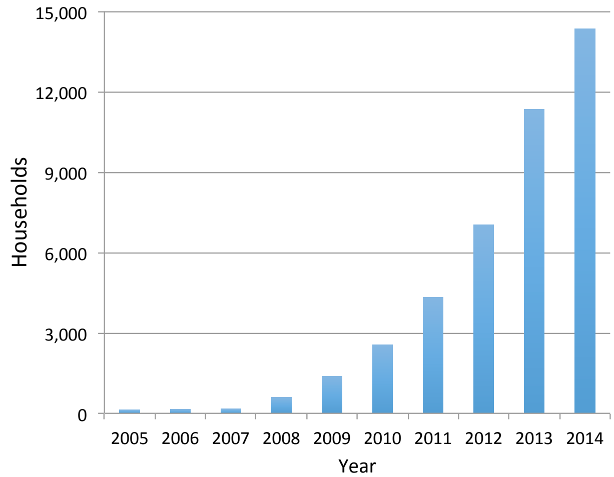


Figure 1: Cumulative households with PV systems in LA. Estimate constructed using data from [21, 22]. (See Appendix A.)

Boulder was selected due to recent developments there regarding a potential municipal electric utility. The citizens of Boulder have voted to create a municipal utility if the current utility cannot meet their requirements for increased service and decreased environmental impact [23]. The city of Boulder is currently attempting to purchase the transmission and distribution infrastructure from the incumbent utility.

Similar to LA, Sydney has seen rapid growth in residential PV systems in recent years and represents a large metropolis with high solar potential. Sydney was also chosen for analysis to explore the potential for a death spiral outside of the US, where energy consumption is generally less. A summary of the model inputs used for each city are given in Table 1.

Table 1: Model inputs for each city. Most values are 2015 or 2014 averages. Each city was initialized with 1 defector household. All monetary values in USD.

Variable	**LA**	**Boulder**	**Sydney**
Regular customers (non-DG households)	3,361,031	45,674	1,448,848
Customers with PV	14,344	1,674	153,571
Annual base demand	16,648 kWh	19,721 kWh	7,000 kWh
Annual PV production	12,469 kWh	19,202 kWh	5,694 kWh
Direct PV use	6,211 kWh	7,007 kWh	2,848 kWh
Baseline retail price	20.9¢/kWh	12.5¢/kWh	20.7¢/kWh

Our analysis focuses on PV systems due to their rapidly declining costs and increasing availability. We have also included PV combined with battery systems. For example, if retail prices continue to grow at the recent rate in LA ($\approx 3\%$ over the last three years), price parity between the retail price of electricity and the levelized cost of energy (LCOE) of a typical 5kW PV system will occur as early as 2018 there (Figure 2). Furthermore, for PV and battery systems (10kW of PV with 65kWh of battery) the LCOE of going off-grid will be the same as the retail price of electricity as early as 2037 in LA [7].

3 Methods and model structure

Figure 3 provides a schematic diagram of the model. This figure illustrates the primary system dynamics captured in the model and the essential components of the utility death spiral. The heart of the model is the adoption of PV and battery systems among households, which is detailed in Section 3.1. The model includes three types of households: regular customers; customers with PV; and defectors or off-grid households with PV and battery systems. In addition to the one-way adoption flows, the model recreates the traditional utility business model, outlined in Section 3.2. The imbalances of the cost and revenue exchanges between the utility and customers with and without PV, especially under a net-metering business model, are also illustrated in Figure 3. These imbalances are captured in formulating the retail price of electricity. Together, the three types of households and the retail price of electricity make up the primary outputs of the model.

The model is formulated around two central questions: (i) how do consumers evaluate the adoption of PV and battery

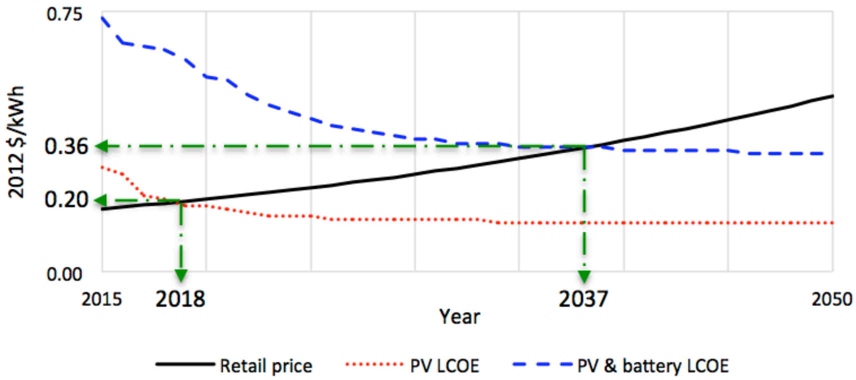


Figure 2: Price parity of PV and battery systems with retail electricity price assuming 3% growth rate [7]

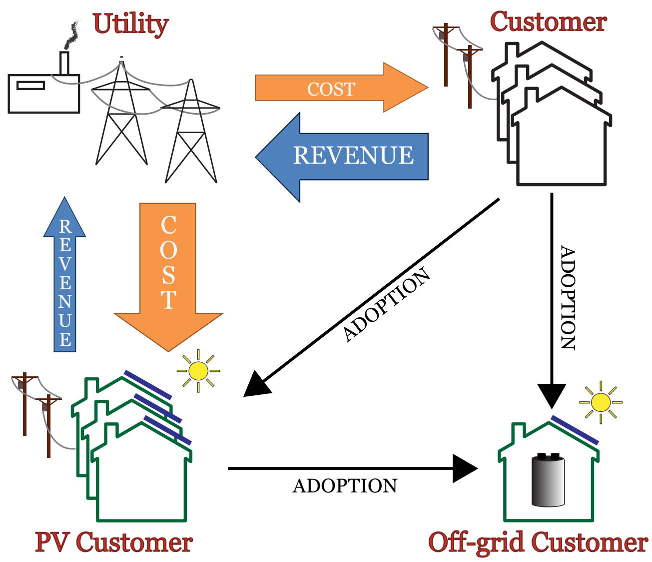


Figure 3: General model schematic diagram. (Figure inspired by [24])

technologies, and (ii) how can we recreate the traditional utility business model while capturing the effects residential PV systems have on utility costs and therefore the retail price of electricity. We consider these questions in the following sections.

3.1 Adoption rates

The technology adoption flows are built with the Bass diffusion model [25]. Developed by Frank Bass, the Bass diffusion model consists of a differential equation that describes how new products are adopted in a population. The adoption rates are a function of both early adopters and late adopters, presented as innovation and imitation flows respectively [26]. Equation 3.1 shows a form of the Bass model for the adoption of a single technology, where $f(t)$ is the rate of change of the installed base fraction (units: time^{-1}), $F(t)$ is the installed base fraction (unit-less), which asymptotically approaches one from zero, p is the coefficient of innovation (unit-less), and q is the coefficient of imitation (unit-less). Figure 4 shows an example how Equation 3.1 can be implemented in a model.

$$\frac{f(t)}{1-F(t)} = p + qF(t) \tag{3.1}$$

The model was constructed in Stella® [27], a system dynamics software that allows for rapidly creating and varying the parameters of differential equations via a graphical interface. As seen in Figure 4: state variables, or stocks, are represented

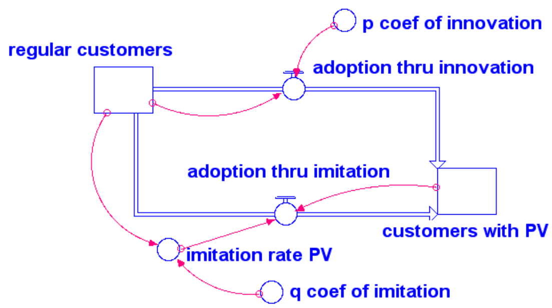


Figure 4: A simple Bass diffusion model in Stella®.

by squares; exchange variables, or flows, are represented by double-line arrows with circular valves in their centers; and auxiliary variables are represented by circles. Single-line arrows allow definition of functional or graphical relationships between variables.

Figure 5 shows the more complicated adoption model used for the work herein. At the broad level, the model consists of three simple Bass diffusion models nested within each other (one for each "adoption" arrow in Figure 3). However, instead of constant coefficients of innovation and imitation, the adoption rates are determined using a financial evaluation.

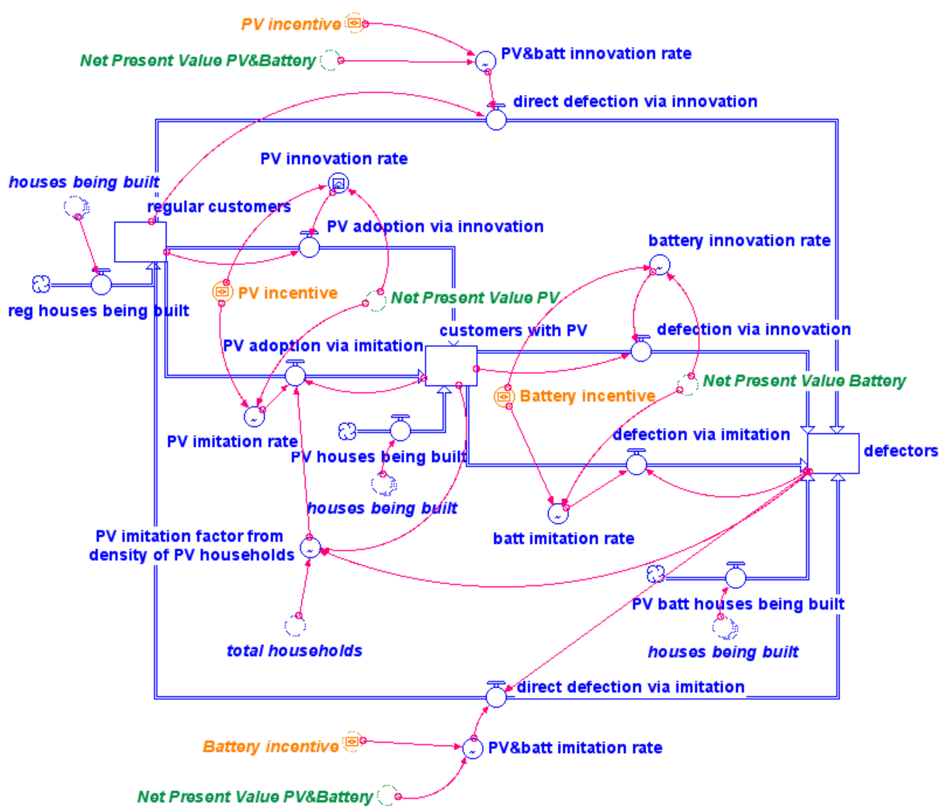


Figure 5: Bass diffusion flows from Stella® model. (The following components have been removed for clarity: flow rate scaling factors k (set equal to one in baseline model); limit on the ratio of PV customers to regular customers; and drain slowing function d.)

Each of the six adoption flow formulas are shown in Equations 3.2 - 3.7, where h is the number of households adopting the technology per year, k is a unit-less constant of proportionality (used for sensitivity analyses), R is graphical rate function (units: time^{-1}), N is number of households where the subscripts reg, PV, and def represent respectively: regular households, PV households, and off-grid households, L is a graphical limit function (unit-less), and d is a graphical drain-slowing function (unit-less). The subscripts on h, k and R distinguish the six adoption flows, with PN for PV innovation, PM for PV imitation, BN for battery innovation, BM for battery imitation, DN for direct defection innovation, and DM for direct defection imitation. Lastly, ρ is a PV density factor that has no effect (equal to one) when there are no PV households, and effectively doubles the imitation flow rate (equal to two) when the number of homes with PV panels (including defectors) is equal to the number of regular households. (No density factor is used for battery system imitation since they are presumed to be installed indoors and therefore do not have the "keeping up with the Jones" effect that highly visible PV panels can affect.)

$$h_{PN} = k_{PN} * R_{PN} * N_{reg} * L * d \tag{3.2}$$

$$h_{PM} = k_{PM} * R_{PM} * N_{PV} * \rho * L * d \tag{3.3}$$

$$h_{BN} = k_{BN} * R_{BN} * N_{PV} * d \tag{3.4}$$

$$h_{BM} = k_{BM} * R_{BM} * N_{def} * d \tag{3.5}$$

$$h_{DN} = k_{DN} * R_{DN} * N_{reg} * L * d \tag{3.6}$$

$$h_{DM} = k_{DM} * R_{DM} * N_{def} * L * d \tag{3.7}$$

The imitation and innovation rates, represented by R, are graphical functions of the net present value (NPV) of each technology (described in Section 3.3). All imitation rates are zero when the NPV is zero (break even point) and grow linearly to 0.4% when the NPV reaches \$10,000. This implies that imitators do not adopt the technology until it is financially beneficial. Innovators, however, have a positive adoption rate for a zero NPV. A positive adoption rate for a zero NPV assumes that innovators are willing to except a negative NPV to be the first in the neighborhood to have the latest technology. (In the case of renewable DG systems, innovators may also be willing to accept a negative NPV because they value reducing greenhouse gas emissions (GHGs), among other reasons.)

The adoption rate for PV innovators is the only adoption rate for which real data is available. Surprisingly, the PV adoption rate of all three cities was approximately 0.5% of total homes in 2014 (values determined from historical data). We assumed that the PV innovation rate will grow linearly to 5% per year when the NPV equals \$10,000 (i.e. the innovator adoption rate grows with the financial benefit). For all the other innovator adoption rates we assumed an initial value of 0.1% of the potential base per year for a zero NPV (i.e. break even point), with growth to 0.5% for NPV equal to \$10,000. These upper and lower bounds were selected as reasonable estimates given the known PV adoption rate of 0.5%.

The limit function, L, limits the number of households with PV systems. As the residential home rental fraction in California is approximately 46% with a growth rate of 1.85% every three years [28], the residential rental fraction in LA was assumed to be 50% on average from 2015 to 2050. Since renters have little financial incentive to install PV systems [29], they are eliminated from the adoption pool for PV systems. Therefore, the ceiling for the number of homes with PV systems as a fraction of the total households was set to 50%. This is achieved in the model using a graphical function that smoothly reduces the PV adoption and direct defection flows to zero as the fraction of households with PV to total households approaches one-half. For ease of comparison the rental fraction was assumed to be 50% in Boulder and Sydney as well.

Lastly, we introduced a first-order drain-slowing function, d, for each adoption flow. The purpose of this function is to create more realistic (lower) adoption rates as the number of potential households approach zero. Once the number of potential households drops below a certain threshold, the drain-slowing function reduces the adoption rate using an 'S' curve - shown in Figure 6. The thresholds for drain-slowing were found through trial-and-error such that a smooth transition to a zero adoption rate occurred as the number of households approached zero. Without the drain-slowing function the adoption rates would be unrealistically high for small numbers of potential households.

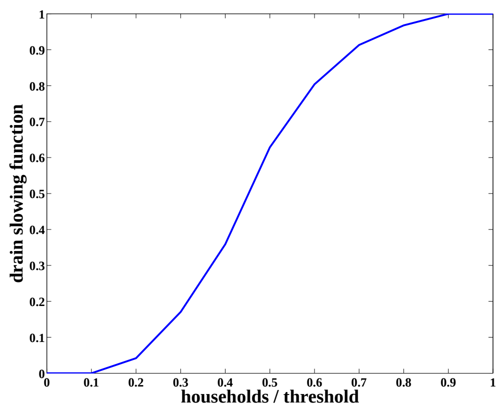


Figure 6: Representative drain slowing function.

3.2 Traditional Utility Business Model

The traditional utility business model consists of a volumetric rate design. The pricing structure is simply the utility's variable costs C_v plus fixed costs C_f, all divided by the total demand D, as shown in Equation 3.8. The variable costs are the same as generation costs, which are the number of customers multiplied by the cost of generating power (or purchasing generated power) times the amount of demand from each customer. The fixed costs consist primarily of transmission and distribution.

$$\text{Retail Price } [\$/kWh] = \frac{C_v + C_f}{D} \tag{3.8}$$

As Figure 7 demonstrates, the actual model is much more complicated than Equation 3.8 indicates. Due to their decreased demand for electricity, customers with PV produce lower revenues for utilities. Additionally, due to the variability that grid-connected PV systems introduce, PV customers can also create higher energy production costs than regular customers[†]. We captured these costs in the model by including the reduced demand of PV customers and an inflated wholesale price for meeting the energy needs of PV customers.

Reference [31] provides annual demand values for a baseline, single family house in LA and Boulder; the average annual demand for Sydney was found in [32]. Determining the demand of a PV household began with determining the energy produced by the average sized residential PV system. The PV production for LA and Boulder was determined using irradiance data from the most recent year with hourly data available from [20]. The annual PV production in Sydney was extrapolated from [33], where a 5kW average system size was assumed from the growth trend in [34]. By combining the hourly data for a simulated household's electricity demand [31] with hourly irradiance data (US: [20]; Australia: [35]) realistic estimates for the electricity directly used by a household from a PV system were made (summarized in Table 1).

To determine a realistic demand value for PV customers we chose to use estimates of the Effective Load Carrying Capability (ELCC) of grid connected PV systems [36]. ELCC is a measure of how effective a generation system is at reducing the demand on the grid without decreasing the grid's reliability in meeting demand. Here we use the percentage definition of ELCC. For example, a 1 MW rated power plant with a 50% ELCC effectively provides 0.5 MW to the grid. The ELCC of PV systems declines with increasing penetration of PV systems. Therefore, our model estimates a PV household's demand with Equation 3.9, where ELCC as a function of the fraction of PV homes to total homes is from [36].

[†]The extent and existence of the added cost of distributed generation for utilities is up for debate. Estimates are few and vary widely (see [24] for examples). [30] enumerates some of the added costs for energy generators, such as *part-load penalty, min-gen penalty,* and *cycling cost.*

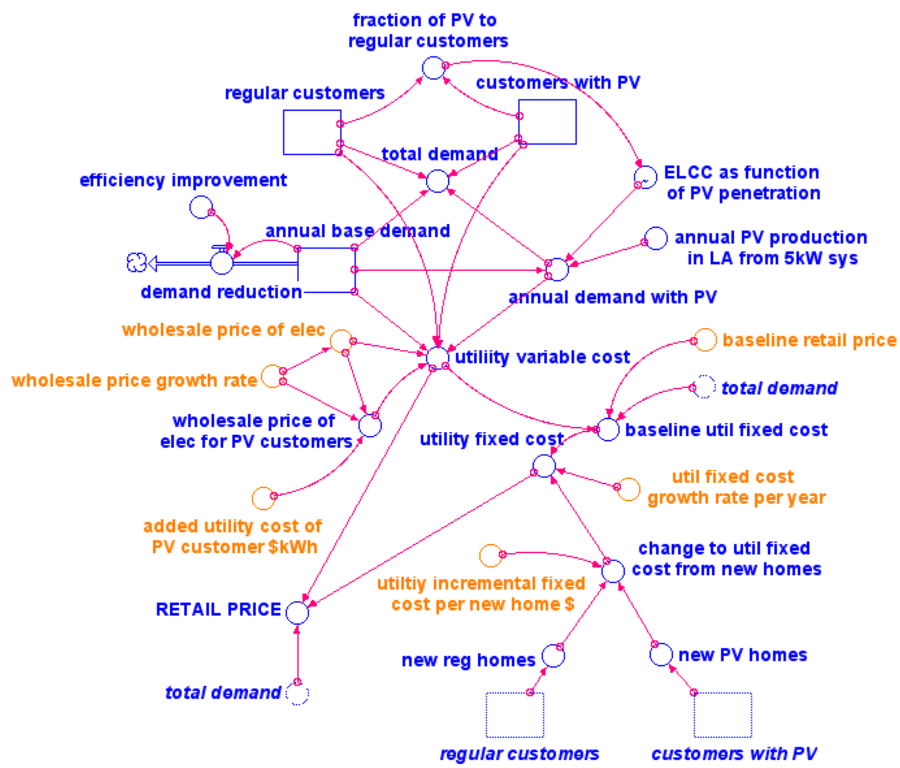


Figure 7: Retail price formulation via the traditional utility business model

$$PV_{demand} = Baseline_{demand} - ELCC \left(\text{as a function of } \frac{PV_{homes}}{total_{homes}} \right) * PV_{production} \tag{3.9}$$

The wholesale price for electricity was determined such that a certain percentage of the retail price came from the utility's generation cost. (The percentage of the generation costs for each city are summarized in Table 2) To simplify the model we assumed that all cost values, including wholesale price, implicitly include the utility's mark-up. This allowed for calibrating the initial cost values to produce the average retail price in each location in recent times (values summarized in Table 1. The wholesale price calibration included the inflated wholesale price for PV customers. The added cost of electricity generation due to DG systems is an open question in the literature. However, from a survey of the few studies that exist on this topic we concluded that an additional 1 ¢/kWh was a reasonable starting point [24, 37, 38]. The wholesale price is assumed to grow 1% per year in the baseline model. A 1% growth rate is based on an average of the US annual average retail price from 2001 to 2014 [9].

Table 2: Model inputs for retail price formulation

Variable	Initial Value	Source and/or assumption
incremental fixed cost per new home	$200/kW with 5kW peak consumption = $1,000/house	[39]
wholesale price growth rate	1%	[40] Apr 2009 - Dec 2013 avgerage 0.8%
fraction of utility costs from generation	LA: 56%; Boulder: 50%; Sydney: 45%	LA [41]; Boulder: estimate; Sydney ref
annual reduction in demand	0.5%	[42] conservative estimate

To capture the improving efficiency of retail customers, lighting systems, and home appliances, the model includes a reduction in the baseline demand as a percentage of the total per year (baseline value of 0.5%). The efficiency improvement is shown graphically in Figure 7 as a drain from the annual base demand.

The last pricing component is the utility's fixed cost. This was straightforward to determine given that we have an initial retail price. From Equation 3.8 the baseline fixed cost is simply the initial retail price times the total initial demand minus the initial variable costs. The baseline fixed cost is allowed to change via two pathways: (i) population growth (see Section 3.5; and (ii) a growth rate, set to a small value for the baseline model (1% growth per year).

3.3 Net Present Value

Figure 8 shows a portion of the model used to calculate the Net Present Value (NPV). NPV represents the difference between the present value of cash inflows and cash outflows for the lifetime of a project, and is commonly used to assess the profitability of investing in a project. For example, the cash inflows of a PV system include the electricity produced by a PV system (valued at the current retail price for Net Metering business model) and the cash outflows include the cost of purchasing the system, or fixed capital investment (FCI) and operation and maintenance costs. Using forecasts from [7] we determined the FCIs for the installed price of PV systems and the price of batteries. The key assumptions in the NPV formulation were:

- investment is financed with 80% of debt
- debt interest rate is 10% throughout the 20-year lifetime of the system, with a 10-year term of loan
- required rate of return is 10%.
- annual operation and maintenance costs of the PV, battery, and PV-battery systems are \$60/kW, \$1.54/kWh (\$100), and \$70/kW respectively

Note that the expected incremental revenue and FCI depend on the size of the installed PV system. The PV systems without batteries in each location are sized using a local average (5kW for LA [43]and Sydney, 9.3kW for Boulder). The PV system size is increased for going offgrid and adding batteries. The offgrid PV system size is determined such that the excess production (i.e. the production that is stored in batteries) is ∼2x the unmet demand without batteries - thus providing a factor 2 margin of safety.

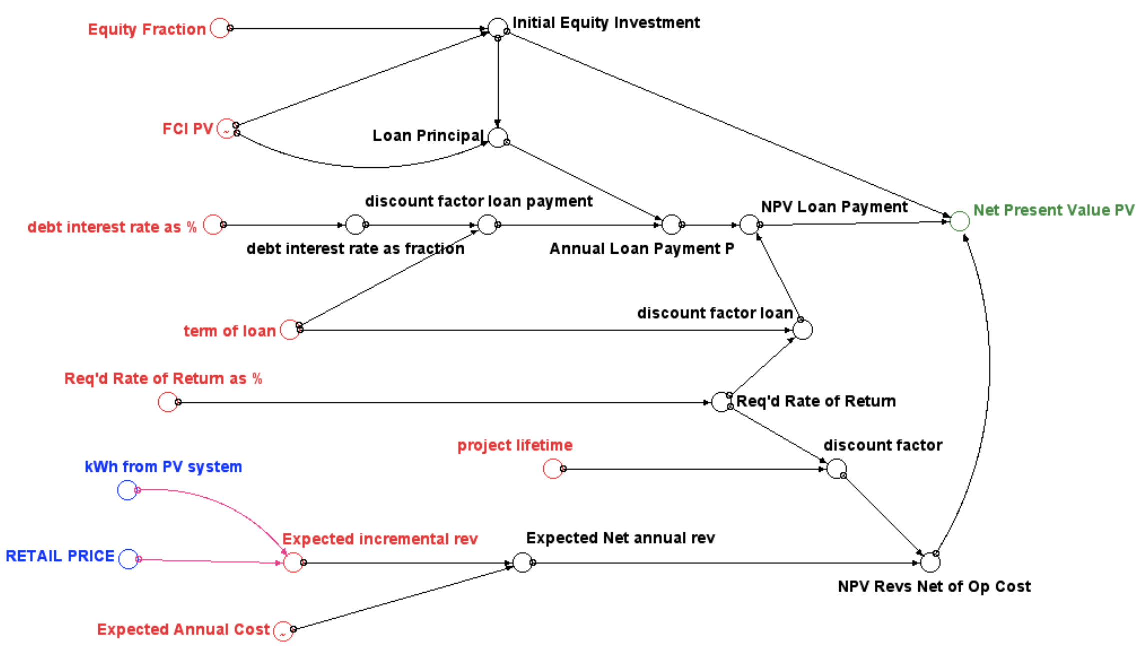


Figure 8: Net Present Value model for PV system.

3.4 Pricing structures

Three different pricing structures were used for comparison in the net present value formulation. The first is a *net metering* structure, which compensates a DG customer with the retail price for excess power generated. Therefore, for a regular customer that does not own a PV system the expected incremental revenue is the potential panel production in kWh times the retail price of electricity in \$/kWh. However, for a regular customer considering an off-grid PV *and* battery system the expected incremental revenue is the customer's entire annual demand time the retail price of electricity (which is the same for all three pricing structures). The model also takes into account the customer with a PV system considering purchasing an off-grid battery system. For this customer the expected incremental revenue of adding batteries to their PV system is the difference of their total demand and the electricity that they use directly from their PV panels, multiplied by the retail rate (see Table 3 for summary).

The two other pricing structures modeled are *wholesale compensation* and *demand charge*. The wholesale compensation structure is built around the premise that by compensating DG customers for excess generation with the wholesale price of electricity rather than the retail price the utility pays a more fair market price. Therefore, for a regular customer purchasing a home PV system the expected incremental revenue is the savings from not paying retail price for the electricity directly used from the panels plus an income from excess production, compensated at the wholesale price. And for a PV customer adding batteries the expected incremental revenue includes the benefit of no longer paying the utility for the difference of the electricity that the customer cannot directly use from their PV system subtracted by the lost income from excess generation.

The demand charge model is an approximation of a pricing structure that already exists in many places, including Boulder as an option to net metering. If we assume that the regular and PV customers have the same peak demand (true for LA and very close for Boulder - data not available for Sydney) then the expected incremental revenue from purchasing a PV system is only a lower energy charge (because the demand charge is unchanged). The lower energy charge for PV customer compared to a regular customer will therefore be approximately the retail price times the direct PV electricity use (all other electricity generated is wasted because it is not stored nor put in to the grid). Therefore the demand charge customer with a PV system considering purchasing a battery system has an expected incremental revenue of the retail price times the difference of their demand and their direct PV use (see Table 3 for summary).

Table 3: expected incremental revenue formulations. Abbreviations: RP ≡ Retail Price, WP ≡ Wholesale Price, PVp ≡ PV production, PVu ≡ PV direct use, D ≡ annual demand

	Net Metering	**Wholesale Compensation**	**Demand Charge**
cust. buying PV sys.	RP * PVp	RP * PVu + WP * (PVp - PVu)	RP * PVu
PV customer buying battery sys.	RP * (D - PVp)	RP * (D - PVu) - WP * (PVp - PVu)	RP * (D - PVu)
cust. buying PV and battery sys.	RP * D	RP * D	RP * D

3.5 Population growth

In addition to the adoption flows of households, the model includes an influx of households via population growth (illustrated in Figure 5 as "houses being built"). For LA the initial value of population growth is set to the value in 2014 (0.6% annual change from 2013 [44]), and then tapers off to half of the initial value in 2050 (assuming that LA will not grow indefinitely). For Boulder and Sydney constant population growth rates of 0.8%/year [45] and 1.8%/year [46] respectively were used.

Which type of house people choose to build is determined by the attractiveness of each type of house, formulated in a logit choice model [47]. The logit function, expressed in Equation 3.10, provides the probability P of a homebuilder choosing alternative i from the set of j choices with an attractiveness x.

$$P_i = \frac{e^{(k_i + Bx_i)}}{\Sigma_j \left(e^{(k_i + Bx_i)}\right)} \tag{3.10}$$

The coefficient B is simply a scaling factor.

We determined the relative attractiveness of a house using the cost of adding a PV or PV and battery system to a new home. Furthermore, given that the construction of many new houses will not be paid for by the same people that will pay the utility bill, we gave regular households an additional higher weighting than houses with DG systems. We achieved this weighting for regular households by doubling the unexplained utility factor, k, relative to households with DG.

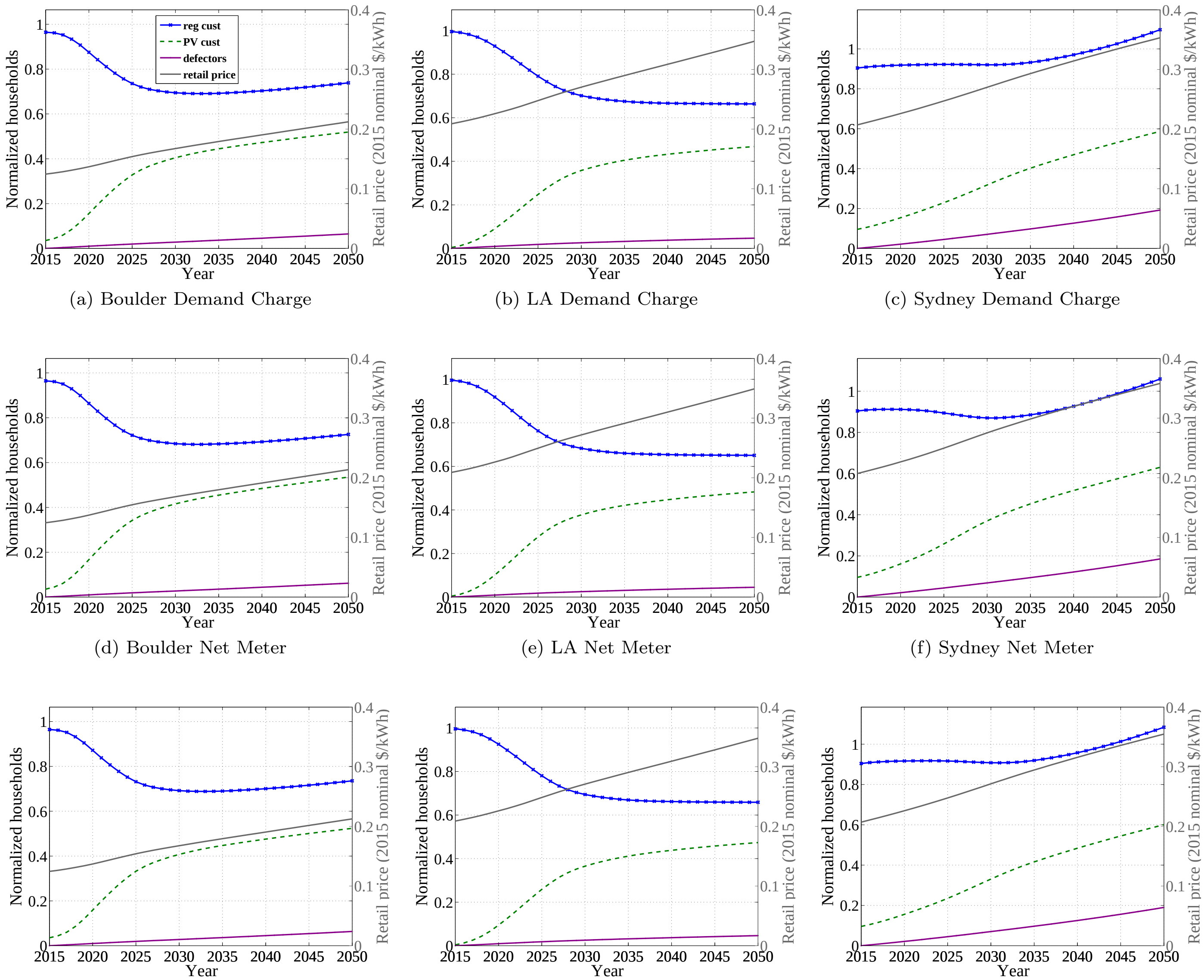
As more homes are added to the system we assumed that the utility's fixed cost will increase. New neighborhoods will require extension of the existing transmission and distribution system, in addition to increasing the load placed on existing infrastructure. We modeled the added cost by adding a flat amount per household to the baseline fixed cost. As expected, reasonable estimates for the scale of this added cost have relatively small impact on the system behavior. Sensitivity analyses indicate that numbers on the order of \$10, \$100, or \$1,000 per household only slightly increase the retail price over time (1 ¢/kWh higher in 2050 for \$1,000 per household vs. \$100 per household). Given that any scale larger than \$1,000 per household is unreasonable, we set the baseline value to $1,000 per household.

4 Results

4.1 Baseline model

Our baseline model indicates that a death spiral is unlikely. From Figure 9 we see that the number of households with PV systems will grow significantly in Boulder and LA until 2030 and then taper off as the threshold of households (rental fraction) for which a PV system is viable is reached. Also, the number of offgrid customers is insignificant compared to the number of grid-connected customers.

For Sydney the results are somewhat different. Sydney exhibits a more steady growth in PV households than the US cities. Sydney also has a greater rate of offgrid technology adoption. If a death spiral were indicated one would see a rapid growth in the off-grid households coupled with comparable drops in the regular and PV customers.



(a) Boulder Demand Charge (b) LA Demand Charge (c) Sydney Demand Charge

(d) Boulder Net Meter (e) LA Net Meter (f) Sydney Net Meter

(g) Boulder Wholesale Comp (h) LA Wholesale Comp (i) Sydney Wholesale Comp

Figure 9: Baseline model results. Left axes are normalized by the total number of households in 2015.

Table 4: Summary of baseline values and sensitivity variables.

Variable	Baseline Value	Sensitivity Value	Note
PV incentive	zero	$5,000 per year	Addition to NPV
Battery incentive	zero	$5,000 per year	Addition to NPV
Imitation scale factor	1	5	Section 3.1
Innovation scale factor	1	5	Section 3.1
Utility fixed cost growth rate	1% per year	5% per year	Section 3.2
Wholesale price growth rate	1% per year	5% per year	Section 3.2
Debt interest rate	10% per year	1% per year	Section 3.3
Equity fraction	0.8	0.1	Section 3.3
Required rate of return	10% per year	1% per year	Section 3.3
Efficiency improvement of customers	0.5% per year	2% per year	Section 3.2
Limit function	Local rental fraction	no limit	Section 3.3

In considering if our baseline model results were reasonable we compared our predicted value of the retail price with historical numbers and some forecasts. The retail price of electricity in the US has grown by an annual average of 1% per year since 2001 [9]. However, in some areas, including California, the retail price of electricity has grown by nearly 3% per year for the last three years. Our baseline model predicts an average annual growth rate of 1.5% to 1.6% out to 2050 for all cities and pricing structures. These values are reasonable given that forecasts range from 0.1% to 3% growth in retail prices [7] and that the US Energy Information Administration's *Annual Energy Outlook 2015* forecasts a 0.5% to 1.0% growth rate in electricity retail prices for the US out to 2040 (depending on scenario) [48].

For Sydney, the percent change in the retail price between 2015 and 2040 predicted by the model was compared to forecasts from the Australian Energy Market Operator. From 2015 to 2040 (after a short drop in retail prices due to the withdrawal of the carbon price) retail prices are projected to grow approximately 30% for the medium demand case and 58% for the low demand case [49]. These values are compared to a growth of 51%, which our model predicts for the same time period in the baseline case.

4.2 Sensitivity analyses

Sensitivity analyses were conducted for ten different model parameters, summarized in Table 4 (the impact of the limit function is analyzed in Section 4.3). With two values for ten parameters and nine different scenarios (three pricing structures and three cities) over 18,000 cases were generated for the four output variables of regular customers, PV customers, defectors, and retail price of electricity. In order to make the analysis tractable the impacts of varying the parameters were measured in terms of the percentage change in the output variables in year 2050.

In terms of **regular customers** the impact of the sensitivity parameters were relatively small changes on the order of two percent or less, with the exception of two parameters. Increasing the *innovation scale factor* from one to five, i.e. increasing the innovator's adoption rate five-fold, decreased the regular customers by an average of 6% across pricing structures and cities. Also, a lower *required rate of return* resulted in an average 3.5% decrease in the regular customers in 2050.

The number of **PV customers** in 2050 in were significantly increased by a higher *efficiency improvement* (average increase in PV customers of 129%). A lower *equity fraction* slightly boosted the PV customers (average increase of 12%). The negative impactors on PV customers had relatively small effects: a lower *required rate of return* (RoR) reduced the PV customers by 12% and higher *utility fixed cost* and *wholesale price* growth rates resulted in the number of PV customers in 2050 being reduced by 9% and 8% respectively.

The decreases in PV customers due to higher utility fixed costs and wholesale price growth rates were accompanied by increases in the number of **defectors** on the order of 30%. In fact, the impacts of the utility fixed costs and wholesale price growth rates were similar across all scenarios. Defectors were also increased by approximately 30% by a greater *innovation scale factor* and nearly 70% by a lower RoR. A higher *efficiency improvement* value is the only parameter that had a significant negative impact on the number of defectors (a decrease of 27%).

As expected there were no parameters that had a significant negative impact on the **retail price**. However, both higher *utility fixed cost* and *wholesale price* growth rates increased the retail price by more than 40% in 2050 and a higher *efficiency improvement* increased the retail price by more than 50%.

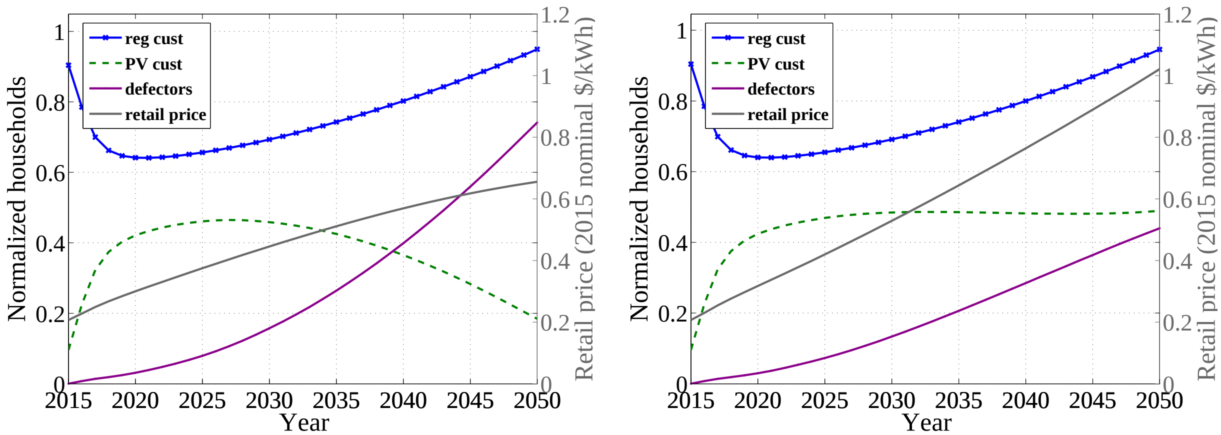
Overall, the parameters with the least individual impact were:

- PV incentive,
- imitation scale factor,
- and equity fraction.

The items with the most individual impact were:

- efficiency improvement,
- utility fixed costs and wholesale price growth rates,
- required rate of return,
- and innovation scale factor.

A greater **efficiency improvement** of customers means that the demand on the utility will be lower with time. With lower demand comes higher retail prices under the traditional business model (see Equation 3.8). Indeed, efficiency improvement had the greatest impact on the retail price of all the sensitivity parameters. When higher retail prices are combined with high adoption rates and high utility costs the results are tipped in favor of PV customers compared to defectors; however, the same combinations with a low efficiency improvement increases the number of defectors significantly. These effects are illustrated in Figure 10, where the high adoption rates are evident in the initial sharp increase in PV customers compared to the baseline plots in Figure 9. These trends are common across cities for the Demand Charge and Wholesale Compensation pricing structures, but less prevalent under the Net Meter structure.



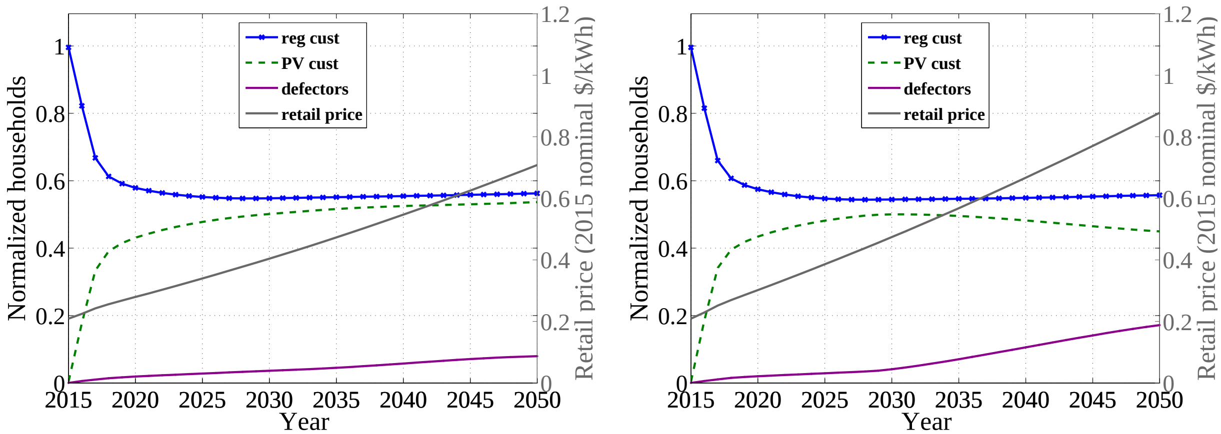
(a) Sydney Demand Charge, 0.5% efficiency improvement (b) Sydney Demand Charge, 2.0% efficiency improvement

Figure 10: Impact of efficiency improvement. Besides efficiency improvement, both cases have the same parameter settings including high adoption rates and utility costs.

Similar to the effect of efficiency improvement, greater **utility costs** increase the retail price as well as lead to more defectors at the cost of PV customers (on average). This effect is shown in Figure 11. Exaggerated results similar to those shown in Figure 11 occur for all cities under the demand charge and wholesale compensation pricing structures; however, the effect of greater utility costs on the number of defectors is muted for the Boulder and Sydney net meter cases.

Unlike the impact of a lower efficiency improvement or higher utility costs, a lower **required rate of return** (RoR) creates more defectors without the accompaniment of a higher retail price (though the results look similar to Figures 10 and 11 in that an increase in defectors comes with a decrease in PV customers, indicating that direct defection from regular customers is rare). Although a lower RoR decreases the amount PV customers in 2050 over all cities and pricing structures on average, the net metering pricing structure results in a *higher* number of PV customers on average with a lower RoR.

A higher **innovation rate** also significantly increases the number of defectors at a cost of PV customers when comparing cases with the innovation rate as the sole difference.



(a) LA Net Meter, 1% utility fixed cost growth rate

(b) LA Net Meter, 5% utility fixed cost growth rate

Figure 11: Impact of utility fixed cost growth rate. Both cases have the same parameter settings except for utility fixed cost growth rate.

Comparing across all cities and pricing structures, the most likely candidate for death spiral is the combination of Boulder and the demand charge pricing structure. The Boulder demand charge combination was the only case that produced scenarios with a greater number of defectors than grid customers at any point in time. These cases highlight the fact that, according to the model, a utility death spiral will require compound factors working against the utility. The common theme across the 48 Boulder demand charge cases with high defectors, in order of impact, are:

- higher 5x adoption rates (48/48 cases),
- lower 1% required rate of return (48/48 cases) ,
- lower 0.5% efficiency improvement (44/48 cases),
- higher utility cost growth rates, fixed and variable (44/48 cases),
- both battery and PV incentives (38/48 cases),
- and lower 1% debt interest (32/48 cases).

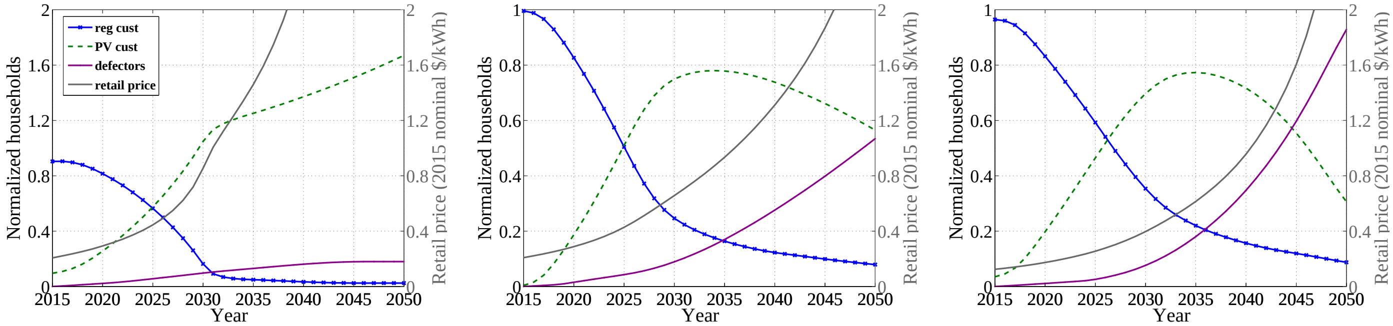
4.3 No limit on number of PV households

It is interesting to explore scenarios where the number of PV households is not limited to a fraction of the total households. With the restriction on the ratio of PV households to total households removed there are numerous cases that lead to a death spiral.

Interestingly, the net meter pricing structure resulted in the fewest number of death spiral cases, (here we define a death spiral as a case where the number of defectors exceed the number of grid customers). A net metering pricing structure creates a greater financial benefit for PV customers staying connected to the grid than the other pricing structures and therefore the flow from PV customers to defectors is retarded under the net metering pricing structure. In fact, LA was the only city with death spiral cases under the net metering pricing structure.

The demand charge structure produced the greatest number of death spirals. The demand charge pricing structure has the opposite effect of the net metering structure, in that when both pricing structures are combined with factors that drive up the retail price and adoption rates the demand charge pricing structure makes the prospect of going off-grid more financially attractive than staying grid-connected.

Comparing across cities, Boulder was the most likely to have a death spiral and Sydney was the least likely candidate. A case for each city is shown in Figure 12, where the least likely city/pricing structure combination for a death spiral is shown on the left, the medium combination in the center, and the most likely death spiral combination on the right.



(a) Sydney Net Meter (b) LA Wholesale Comp (c) Boulder Demand Charge

Figure 12: Comparison of cases with no limit on PV households. All cases have the same parameters: No incentives, high efficiency improvement, high utility costs, and low values for debt interest rate, equity fraction, and RoR.

5 Discussion

Many of the factors that influence a utility's customer retention are outside of a utility's control. Among the most impactful parameters explored in the sensitivity analyses, three out of four are entirely up to consumers: the efficiency improvement of customers, the required rate of return of customers, and the rate of adoption by innovators. Electricity consumers are becoming more conscious of their energy use. In some cases, a consumer's electricity consumption is reduced simply by purchasing more energy efficient appliances and electronics, which are becoming more prevalent in the market. More consumers are also beginning to value reducing their greenhouse gas emissions and therefore lower their RoR when considering a home PV system. And rapidly declining PV prices in recent times have boosted adoption by innovators.

Utilities can, however, control the pricing structure and to some extent their costs. Obviously, rising fuel costs as well as renewable energy standards that might require purchasing more expensive energy are difficult for utilities to affect. But the model results indicate that the utility pricing structure will have a large impact on consumers decisions. The utility pricing structure directly affects the net present value of distributed generation and off-grid systems for consumers. In the future, as DG and battery system costs come down, utilities may have to strike a balance between maintaining profits while providing DG customers with reasonable compensation for excess generation.

6 Conclusions

A utility death spiral due to solar photovoltaic and battery systems is highly unlikely. The model only indicated death spirals, in which the number of defectors is greater than the number of grid-connected customers, in cases with combinations of extremely high adoption rates, high utility costs, and low financial parameters such as the customers' required rate of return.

We explored the impact of three different pricing structures with the traditional utility business model for three different cities. It is clear that the pricing structure can have a significant impact on a utility's customer retention. Utilities will most likely have ample time to adjust their business model and pricing structures to maintain profits and prevent grid-defection. Indeed, utilities are already adopting alternative pricing structures, indicating that they are adapting to the rapidly changing market. Some ways that utilities could reduce costs while attracting DG customers include rewarding customers for providing peak power, reducing line congestion, and deferring infrastructure investments [1].

It is a time of rapid change for the utility industry in the US. Though a death spiral may not be a viable threat to utilities, customers are rapidly becoming prosumers and more aware of where and how their electricity is produced. Utilities are regulated monopolies that are protected for the public good. They sometimes have conflicting interests of obtaining a satisfactory rate of return for investors while providing affordable, reliable electricity service. In the future, if distributed generation and storage technologies provide a more attractive option than grid power to consumers - while simultaneously achieving societal goals such as reducing greenhouse gas emissions - will it still be in the public's best interest to protect private utilities from extinction? Only time will tell.

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Boulder employee for permit data

References

[1] F. A. Felder and R. Athawale, "The life and death of the utility death spiral," The Electricity Journal, vol. 27, no. 6, 2014.

[2] R. Hemphill and K. Costello, The death spiral: An assessment of its likelihood in electric utilities. Office of Science and Technical Information, US Department of Energy, 1987.

[3] R. Khalilpour and A. Vassallo, "Leaving the grid: An ambition or a real choice?," Energy Policy, 2015.

[4] E. Graffy and S. Kihm, "Does disruptive competition mean a death spiral for electric utilities?," Energy Law Journal, vol. 35, no. 1, 2014.

[5] C. A. Severance, "A practical, affordable (and least business risk) plan to achieve "80% clean electricity" by 2035," The Electricity Journal, 2011.

[6] J. Jean, P. Brown, R. Jaffe, T. Buonassisi, and V. Bulovic, "Pathways for solar photovolatics," Energy and Environmental Science, vol. 8, 2015.

[7] "The economics of grid defection," tech. rep., Rocky Mountain Institute, Homer Energy, and Cohnreznick Think Energy, 2014.

[8] Bureau of Labor Statistics, "Average energy prices, los angeles-riverside-orange county." http://www.bls.gov/regions/west/news-release/.

[9] US Energy Information Administration, "Residential retail electricity price." http://www.eia.gov/electricity/data/browser/, 2015.

[10] D. Raskin, "Getting distributed generation right: a response to "does disruptive competition mean a death spiral for electric utilities?"," Energy Law Journal, 2014.

[11] F. P. Sioshansi, Distributed generation and its implications for the utility industry, ch. Introduction. Elsevier Inc., 2014.

[12] "Will solar cause a 'death spiral' for utilities?." Forbes.com, Jan. 15 2015.

[13] D. P. Dubal, O. Ayyad, V. Ruiz, and P. G. ÌĄmez Romero, "Hybrid energy storage: the merging of battery and supercapacitor chemistries," Chemical Society Reviews, vol. 44, 2015.

[14] M. A. Pellow, C. J. M. Emmott, C. J. Barnhart, and S. M. Benson, "Hydrogen or batteries for grid storage? a net energy analysis," Energy and Environmental Science, vol. 8, 2015.

[15] P. Roy and S. K. Srivastava, "Nanostructured anode materials for lithium ion batteries," Journal of Materials Chemistry A, 2014.

[16] Z. Ma, X. Yuan, L. Li, Z.-F. Ma, D. P. Wilkinson, L. Zhang, and J. Zhang, "A review of cathode materials and structures for rechargeable lithium–air batteries," Energy and Environmental Science, 2015.

[17] D. L. Chandler, "New manufacturing approach slices lithium-ion battery cost in half." www.phys.org, June 2015.

[18] N. Armaroli and V. Balzani, "Towards an electricity-powered world," Energy and Environmental Science, vol. 4, 2011.

[19] K. W. Costello, "Major challenges of distributed generation for state utility regulators," The Electricity Journal, 2015.

[20] National Renewable Energy Laboratory, "National Solar Radiation Database." http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2010/, 2015.

[21] B. Davis, T. Madsen, and M. Kinman, "California's solar cities," tech. rep., Frontier Group, Environment California Research and Policy Center, 2012.

[22] Go Solar California, "Souther California Edison solar PV statistics." https://www.californiasolarstatistics.ca.gov/reports/monthly 2015.

[23] K. Crandall, H. Bailey, Y. Gichon, and J. Koehn, Distributed generation and its implications for the utility industry, ch. 22: Turning a vision to reality: Boulder's utility of the future. Elsevier Inc., 2014.

[24] Hansen et al., "A review of solar pv benefit and cost studies, 2nd ed.," tech. rep., Electricity Innovation Lab, Rocky Mountain Institute, 2013.

[25] F. M. Bass, "A new product growth for model consumer durables," Management Science, vol. 15, pp. 215–227, 1969.

[26] E. Drury, P. Denholm, and R. Margolis, "Modeling the u.s. rooftop photovoltaics market," in National Solar Conference, NREL, 2010.

[27] isee Systems, "Stella dynamic modeling software." http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx.

[28] California Department of Numbers, "Residential Rent Statistics for California." http://www.deptofnumbers.com/rent/california/, 2015.

[29] P. Denholm, E. Drury, and R. Margolis, "The solar deployment system (solards) model: Documentation and sample results," tech. rep., National Renewable Energy Laboratory, 2009.

[30] O. Q. Wu and R. Kapuscinski, "Curtailing intermittent generation in electrical systems," Manufacturing and service operations management, vol. 15, no. 4, 2013.

[31] B. Hendron and C. Engebrecht, "Building america house simulation protocols," tech. rep., National Renewable Energy Laboratory, DOE Building Technologies Program, 2010. Database: http://en.openei.org/datasets/files/961/pub/.

[32] Independent Pricing and Regulatory Tribunal of New South Wales, "Determinants of residential energy and water consumption in sydney and surrounds," tech. rep., 2011.

[33] Clean Energy Council, Australia, "Consumer guide to buying household solar panels." Volume 14, August 2011.

[34] Clean Energy Council, Australia, "Clean energy australia report 2014."

[35] Australian Bureau of Meteorology, "One minute solar data: Wagga station." http://reg.bom.gov.au/climate/reg/oneminsolar/.

[36] Perez et al., "Effective load-carrying capability of photovoltaics in the united states," tech. rep., National Renewable Energy Laboratory, 2006.

[37] California public utilities commision, "Technical potential for local distributed photovoltaics in california, preliminary assessment," tech. rep., Energy and Environmental Economics, Inc., 2012.

[38] "Costs and benefits of distributed solar generation on the public service company of colorado system," tech. rep., Xcel Energy, Inc., 2013.

[39] Navigant Consulting, Inc., "Distributed generation integration cost study," tech. rep., California Energy Commission, 2013.

[40] US Energy Information Administration, "Wholesale electricity price, historical data." http://www.eia.gov/electricity/wholesale/#history.

[41] Souther California Edison, "Utility bill breakdown." https://www.sce.com/, 2015.

[42] World Energy Council, "Average electricity consumption of households per capita." https://www.wec-indicators.enerdata.eu/electricity-use-per-capita.html, 2013.

[43] San Diego County Solar, "Typical PV system size in southern California." http://sandiegocountysolar.com/how-big-are-solar-panels/, 2015.

[44] US Census Bureau, "Population and household data for LA county." http://quickfacts.census.gov/qfd/states/06/06037.html, 2015.

[45] C. Harald and J. Pinsonneault, "Demographic profile, boulder, colorado," tech. rep., Boulder Economic Council, 2011.

[46] Australian Bureau of Statistics, "2011 census." http://www.censusdata.abs.gov.au/.

[47] R. D. Luce, Individual Choice Behavior: A Theoretical Analysis. John Wiley and Sons, 1959.

[48] US Energy Information Administration, "Annual energy outlook 2015." http://www.eia.gov.

[49] A. Frontier Economics Pty. Ltd., "Electricity market forecasts," tech. rep., Australian Energy Market Operator, 2015.