Investigating the Effect of Tariff Revision Process on Electricity Retail Tariff and Utilities Death Spiral

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Received 25 Aug. 2022 Received in revised form 02 Nov. 2022 Accepted 18 Nov. 2022

Type of Article: Research paper

***Abstract*—The accelerating deployment of Distributed Energy Resources (DERs) is eating away at electric utilities sales and revenues. It is feared that attempting to recover their lost revenue through raising tariffs may trap utilities in a "Death Spiral". In this paper, the interaction between utilities, consumers, and DERs is modeled using System Dynamics (SD) to investigate the impact of distributed renewable resources on utilities. Furthermore, a new model for electricity tariff revision has been developed that captures regulatory and organizational delays. The model has been simulated with the latest available data and sensitivity analysis has been carried out for important parameters. Results suggest that while the death spiral is not an immediate threat under normal conditions, the delay in price revision can introduce considerable fluctuation in electricity tariff, which worsens when the delay increases. Another outcome of this study is that population growth has the potential to mitigate the effects of death spiral. On the flip side, utilities serving areas with a low rate of population growth, such as Europe, face a more significant threat from distributed resources.**

***Keywords*: Distributed Generation, Utilities Business Model, System Dynamics, Utilities death Spiral**

I. INTRODUCTION

AFTER several decades of steady growth, the golden age of electric utility industries came to an end in the 70s. The oil crisis coupled with high inflation rates increased utilities' expenditures, while stagnant demand sent their income downhill. As a result, utilities attempted to increase electricity tariffs which raised concern among regulators and experts. They feared that increasing tariffs would fail to bring them the expected income and suppress the demand even further. It was suspected that utilities would be trapped in a vicious cycle of increased price and reduced income, named "Death Spiral", the same fate as streetcar utilities during the early decades of the 20th century. Although utilities didn't go bankrupt, the crisis had lasting effects on the power industry such as the shift to small-scale generation and power system restructuring [1].

In recent years, the rapid growth of Distributed Energy Resources (DERs), especially rooftop solar PVs, is threatening electric utilities once again. Increased number of rooftop PVs will result in reduced utility sales while the cost of providing energy and maintaining the distribution system remains constant, if not climbing. In this situation, utilities may attempt to increase electricity tariffs in order to recover lost revenue, which will encourage more consumers to install rooftop PVs, thus reducing sales even more. The difference is that in the previous crisis, customers had to substantially reduce their power consumption for the death spiral to gain traction, which is not possible since modern societies rely heavily on electricity. This time, however, customers can consume the same amount of electricity, while reducing their purchases from utilities dramatically. This means that electric utilities are facing increased competition, an unfamiliar situation that is not compatible with their current business model. The question is how this new kind of competition (which is described as disruptive by some researchers [2]) affects the utilities, electricity consumers, and the power industry as a whole.

A. Background

There has been extensive study on the effects of DERs on power systems [3], the majority of which focus on

[DOI: 10.61186/joc.17.3.37]

technical aspects such as protection [4], [5], grid operation [6], [7], planning [8], etc. However, many experts had pointed out that there is a potentially significant dynamic relationship between DERs, utilities, and customers [9]–[12], which these studies often overlook by investigating each part of the system separately. A strand of research deals with this issue by including the causal relationship between major parameters in the model, e.g., DER price, electricity tariffs, and customers' economic decisions, mainly with the help of the System Dynamics (SD) modeling approach [13]. This category of studies primarily deals with the "death spiral" phenomenon and can be divided into three subcategories: The mechanism of the effect, the role of tariff design, and introduction of new alternative business models and policies. Most of the research effort is concerned with the mechanism of the death spiral. These articles investigate the effect of different parameters and feedback loops on utility sales, electricity prices, and DER uptake.

The effect of customers price elasticity, population growth and solar potential on the utilities' death spiral is investigated in [14]. The study introduced several indicators of death spiral and evaluated their sensitivity to input parameters, using an SD model. Simulation results support the possibility of death spiral in certain scenarios, such as low population growth or high PV potential. Laws et al. [15] developed a complex SD model to investigate the death spiral. Their findings indicate that death spiral is unlikely in normal situations and only extreme conditions can trigger it. Results also show that net-metering will discourage customers to become defectors compared to other billing schema, contrary to the popular opinion that net-metering is the main driver behind death spiral. In [16], the effect of solar DGs on utilities and consumers in Columbia and several policies to smoothly penetrate them into the power industry has been studied. Results suggest that with systemic intervention, the death spiral can be avoided in medium term. However, in long term, it is claimed to be inevitable. The Authors also investigate the potential effect of rooftop solar on the power industry through an improved and more detailed SD model [17]. The study finds that renewable energies could create disruption in generation sector by driving the prices down and at the same time, reducing sales. On the other hand, Young et al. [18] estimated that the potential network investment cost reductions are capable of completely negating the lost revenue due to reduced energy sales in Sydney, Australia.

The death spiral has been investigated from a different perspective in [19], focusing on the impact of network effects in the transition toward a more decentralized power system. The study concludes that the network effect could potentially encourage customers to form microgrids and become more independent of the main grid, accelerating the effect of the death spiral. [20] builds upon the model developed in [19] and investigates the dynamic relation of death spiral and distributive justice of electricity costs, finding that compared to other billing methods such as net purchase and sale, net-metering could induce the death spiral more strongly, while the resulting installed capacity of PVs remain largely similar. Cai et al. [21] also find that the death spiral doesn't have a significant effect on PV adoption rate while the customers' confidence in PV systems and technology is the key factor. However, net-metering costs were found rapidly raising with increase in PV adoption, which indicate the flaw with volumetric tariffs. Satchwell et al. [22] found the impact of distributed PV on electricity retail price, not significant enough to cause a death spiral, although the study overlooked important dynamics of the system. Furthermore, results showed that the effect of distributed PV would be more strongly felt by utilities shareholders.

Many of the papers point to the fact that electricity pricing plays an important role in utilities death spiral [23]. Therefore, another group of articles deals with the way electricity pricing affects the penetration of distributed generation and utility income. Darghouth et al. [24] use empirical data to calculate bill savings caused by installing rooftop PV systems under different electricity metering methods and rate designs. They mainly focus on net-metering and compare it with three alternatives and found that despite encouraging customers to install smaller PV systems, inclining block rates provide greater support for PV adoption among high-usage customers. The study also suggests that net-metering induces significant variation in bill saving among customers, while FiT with MPR levels exhibits more consistency and simplicity, albeit with notably lower bill savings for customers. In another study, Darghouth et al. [25] focus on time-variant rate design and argue that widespread penetration of rooftop PVs may shift the time of peak demand and reduce bill saving for customers. This will slow down the PV installation process and prevent the death spiral. Results also indicate that adding a fixed charge to customer bills could substantially reduce PV deployment. In [26], the combined effect of DERs and EVs on grid cost recovery has been investigated, using a non-cooperative game structure between the regulator and four classes of network users. The study concludes that the penetration of EVs could compensate lost grid revenue caused by load-defecting prosumers. Furthermore, results indicate that the more a tariff structure gives incentives for DERs,

[DOI: 10.61186/joc.17.3.37]

the less beneficial it is for EVs. Eid et al. [27] find that energy charging combined with net-metering decreases utility income considerably and causes cross subsidies. This effect is aggravated by larger timeframes for net metering since the utility is acting as a storage for the PV system. Therefore, the authors suggest shorter timeframes, although claiming that charging for capacity is superior since it doesn't induce cross subsidies and shows better cost causality. Castaneda et al. [28] claim that reducing Feed-in Tariff (FiT) would decrease PV investment but results in more battery installation and subsequently reduced utility demand, whereas another study found that the FiT could be abolished soon if self-sufficiency rates increase, while the expansion of PVs continues [29]. Felder and Athawale [30] also largely blame the rate design for death spiral, claiming that separating fixed, and variable costs can effectively defuse the threat. However, they suggested that for political reasons, only consumers with DG should be subjected to it. They also suggest the possibility of changing utilities business model to include installing solar systems, although arguing that it may create an unbalanced playing field and should be practiced with caution.

Most studies point to the decisive role of regulators and policymakers in shaping the future of utilities [9], [11], [31]. Rochlin [32] argues that the current regulatory practice of funding microgrids and other social goals in the expense of utilities is not sustainable and may lead to a false economic signal for leaving the grid. Policy and regulatory frameworks have been found to be more important in shaping business models than technology factors by Burger and Luke [33]. In [34] several alternative business models to compensate the utilities lost income and prevent the death spiral were examined in addition to simulating the status quo. The results suggest that utilities are better off investing in distributed solar generation themselves or provide services if they want to avoid the risk. By comparing the business models in developing and industrialized countries, Engelken et al. [35] concluded that business models for renewable energies in the latter group are more based on cooperation and environmental concerns, whereas in the developing countries microfinance and more individual goals are the primary drivers of business models. Additionally, lack of empirical data in developing countries hinder comprehensive study and innovation in this subject. Based on the study conducted in [22], Satchwell et al. [36] assess different approaches to mitigate the impact of distributed PV on utilities financial performance. They found that many of the energy efficiency mitigation measures are also effective in preventing a death spiral, although they have certain tradeoffs.

Several researchers such as Graffy and Kihm[2] and Riesz and Gilmore [37] argue that the best path for utilities is to shift from cost recovery to value creation strategies and not rely on regulatory support. The authors of [2] claim that continuing to pursue conventional methods such as risk aversion and accounting cost recovery will probably make utilities more vulnerable in long run. They encourage utilities to follow the example of the cable industry in value creation, to successfully navigate the incoming change in the power industry.

B. Research Gaps and Contribution

The review of the research background reveals some important points: first, many of them find that the risk of a death spiral for the utilities is not severe in the near future. Second, the role of tariff structure, especially the harm of net-metering to utilities and other customers is highlighted almost unanimously. However, delays, which significantly impact the system behavior are absent from them. In this paper, we attempt to address the issue by incorporating related system delays in the model. The most important contribution of this study in this regard is the proposed novel model for price revision. We have also included population growth in the model, which is also missing in the reviewed articles, as it has the potential to compensate for the effects of the death spiral. The effect of these proposed additions to the existing models is investigated through extensive sensitivity analysis and results prove their significance. Moreover, the response of customers to price changes due to price elasticity of demand has been also incorporated in the model. However, simulation results show that it has a negligible effect on the outcome. In short, the contributions of this study can be summarized as follows:

1. A novel and more realistic tariff revision model has been developed to represent real-life delays.
2. The effect of population growth on the death spiral phenomenon is investigated.
3. The price elasticity of demand and the response of consumers to price adjustments is integrated into the model.

C. Paper Structure

The rest of this paper is structured as follows: First, a general overview of the proposed model and its assumptions is presented in section II. Then, to better understand the whole model, its detailed description is divided into 3 sections for Customers, Utility Business Model and Distributed Energy Resources (DER). Moreover, input data and the result of simulating the models are presented along with sensitivity analysis on selected parameters in Section VI. Finally, the findings are concluded in Section VII.

II. MODEL

In this paper, we investigate the effect of DERs on utilities sales and finances by developing a comprehensive model of the interaction between DERs, utilities, and their customers.

A. Assumptions

To focus the scope of this study, a couple of simplifying assumptions for developing the model, without damaging the reliability of the results, has been made:

- The utility is a regulated monopoly that is permitted a fixed rate of return on their expenditure
- The study is focused on rooftop solar PVs and residential consumers.
- Base demand for customers doesn't change during the simulation period.
- Utility fixed costs remain unchanged during the simulation period.
- Utility variable costs only include the cost of power generation or purchase from the power market.
- The utility recovers its costs through volumetric schemes, meaning that the customers don't pay fixed charges and are only billed based on their energy consumption.
- The total number of households increases relative to population growth.

The proposed model is structured using System Dynamics (SD) [13] to capture the causal relations between system components. System Dynamics is a common approach among researchers for analyzing complex systems over time and has been extensively used to study the power system's long-term dynamics and the death spiral phenomenon [38]–[41]. A brief introduction to System Dynamic can be found in the Appendix.

B. Regulatory frameworks

As stated before, the utility modeled in this paper is an Investor-Owned Utility (IOU) and a regulated monopoly as is the case with the utilities in the United States [42]. The regulatory structure in the U.S. requires the electricity price issued to customers to be determined in a process called rate case proceeding. In the rate case proceeding, an IOU files a petition with its jurisdiction area regulatory commission to modify its rates and charges [43]–[45]. The commission investigates the utility's financial report and determines the total amount the utility is authorized to collect usually based on an agreed-upon fixed rate of return on expenditures. Based on this, the commission and the utility determine the rates for different customer classes [46].

C. Fundamental Concepts

The simplified Causal Loop Diagram of the developed model is depicted in Fig. 1, with three fundamental feedback loops. It is easy to understand that when the number of customers with PV increases, utility sales decline since these customers produce a fraction of their energy requirements on-site. This will reduce the utility's income. Although declining sales will reduce variable costs (Loop B1), it would not be sufficient, because the fixed costs which contribute to a significant portion of total utility costs, stay unchanged. The utility now must recover its costs from fewer kWhs sold.

Their main option based on previous incidents is to increase the electricity retail tariff. However, higher retail price increases the attractiveness of using solar PV systems and accelerate their adoption and utility's sale drop. This is a positive feedback loop (reinforcing loop in system dynamics terms), which could potentially exponentially increase the electricity retail price and the number of customers with PVs, if left unrestrained. Another important feedback loop that has been mentioned in many studies is the R2 loop in fig. 1. It represents the fact that as PV installations increase, the overall cost of installing PVs will drop due to various measures such as increased sales for PV manufacturers, as well as installing companies becoming more experienced and efficient. As a result, the attractiveness of PVs increases, creating another reinforcing loop.

These loops represent the main concept of the utility death spiral that has been studied in previous research articles. However, this model has three shortcomings that we attempt to address in this study:

1. The process of changing the electricity tariff (rate case proceeding) is not instantaneous. In other words, it would take months or even years for the regulatory board to approve an increase in the tariff [44], [46], [47]. In the meantime, the utility is suffering from a budget deficit due to the continuously increasing installation of PVs. This has the potential to create an additional dynamic in the system which will be thoroughly discussed later in the paper.
2. Population growth creates new customers for the utility that can compensate for the sales lost to DERs.
3. The customers without PV will reduce their electricity consumption when the retail price increases, due to the negative price elasticity of the demand, which may amplify the utility's sale reduction.

[DOI: 10.61186/joc.17.3.37]

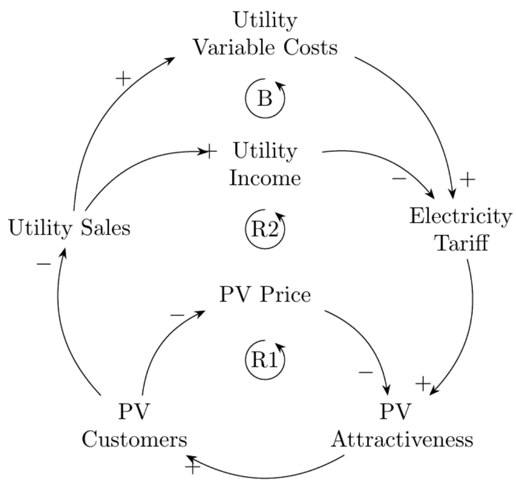

Figure 1. Simplified CLD of the model showing the main feedback loops

The developed model is a large and comprehensive system that can be divided into three submodels: 1-customers model, 2-utility model, and the DERs model. These submodels are discussed in detail in the following sections. The symbols that are used in the following formulations and their description are presented in the following nomenclator table.

Symbol	Description
indices	
t	time
r	Regular consumers
p	prosumers
d	defectors
pv	PV system
b	battery
variables	
m	Total market potential for a product/concept
$F(t)$	fraction of all the consumers that have adopted the new product/concept
$X(t)$	Number of potential consumers who have not yet adopted the new product/concept
$A(t)$	Number of consumers who have already adopted the new product/concept
p	coefficient of innovation
q	coefficient of imitation
$e(t)$	Logistic (sigmoid) function to limit the Bass model coefficients
P_e	price of electricity
ϵ	price elasticity of demand
D_*	Average monthly demand of each consumption type
N_*	Number of consumers adopting each consumption type or size of DER component
C_{fix}	Utility fixed costs
G	Total Amount of power that the utility should procure
π_g	The unit price of procuring electricity
$Sale$	Total utility sale
$Loss$	Electricity transmission and distribution loss
R_{act}	Actual utility revenue
R_{act}	Expected utility revenue
$RD(t)$	Utility revenue deficit
$\Delta P_{e,ind}(t)$	Required change in electricity tariff
$\rho(t,i)$	Revision interval function
N_*	Size of the PV system
P_*	price of a unit (1kW) PV or battery
$NPV_{I,pv}$	net present value of the total income that a unit of PV generates in its lifetime
T_*	Lifetime of the PV or battery system
i	discount/interest rate
$I_{pv,m}$	monthly income of a unit of PV
$Gen_{pv,m}$	monthly energy generation of a unit PV
M_{rel}	reliability margin
α_d	fraction of daily demand that should be supplied from the batteries for defectors

III. Customers Model

The interaction between electricity customers and the utility is modeled from two perspectives:

1. How much of their electricity consumption

[DOI: 10.61186/joc.17.3.37]

comes from the grid

2. How do they react to utility price changes

The first aspect deals with installing DERs in response to price changes and "Consumption Types" as discussed next, while the second one is focused on the short-term reaction to price changes and direct price elasticity. Installing DERs is the major route for the utility death spiral and investigated in previous works. However, the effect of short-term price elasticity of demand on the utility death spiral has not been investigated before.

We should emphasize that not all customers of a utility in a given region can install PV systems. This is mainly, among other reasons, due to shading and the limited roof area of high-rises, especially in populated cities. Thus, the proposed model is structured to limit the maximum fraction of customers that have PV systems to a fixed predefined value. Additionally, we incorporated population growth in the customers' submodel, as our preliminary studies suggested that it could compensate for the lost sales of utilities. By including population growth, we aim to model real life circumstances more accurately and investigate their impact on the results.

A. Consumption Types

Electricity consumers could have different characteristics based on how they interact with the utility. Accordingly, three types of electricity customers are considered in this research:

- Regular Consumers: They rely on the utility for all their electricity consumption.
- Prosumers: They have a rooftop photovoltaic system which covers a portion of their electricity consumption. Therefore, they stay connected to the grid, but receive less energy from it.
- Defectors: They have a stand-alone DER and are completely disconnected from the utility.

We have used the Bass model [48] to simulate consumers shift from one type to another. It is important to note that this study is solely focused on electricity consumption and the above-mentioned customer types merely differ on how they procure their electricity demand. The Bass model is the most widely applied new-product diffusion model in a market and is formulated by:

$$\frac{dF(t)}{dt} = \big(p + qF(t)\big)\big(1 - F(t)\big) \qquad (1)$$

where $F(t)$ stands for the fraction of all the consumers that has adopted the new product/concept, while p and q are the coefficients of innovation and imitation, respectively. The Bass model states that the number of consumers who adopt a new product ($\frac{dF(t)}{dt}$) is determined

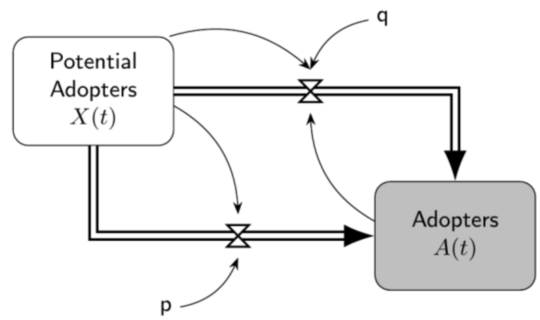

Figure 2. Bass model Stock & Flow diagram

by the combination of:

- Innovators $p\big(1 - F(t)\big)$: who are attracted by its sheer advantages
- Imitators $qF(t)\big(1 - F(t)\big)$: who are persuaded by its previous adopters

It should be noted that this formulation is applied to a potential market as a whole, not individual consumers. Moreover, innovators and imitators are not distinct consumption types in addition to the three previously defined consumption types. But rather, they are two pathways for consumers to change their consumption type as can be seen in the stock and flow representation of the Bass model in Fig. 2.

In this figure, $X(t)$ represents the total number of potential consumers who have not yet adopted and $A(t)$ stands for the number of consumers who have already adopted the new product. The upper and lower paths represent adoption through imitation and innovation respectively. Using real numbers instead of fractions, we can rewrite (1) based on the notations of Fig. 2 as:

$$A(t) = \int X(t)\left(p + q\frac{A(t)}{m}\right)dt \qquad (2)$$

Where m represents total market potential for the product/concept and equals to $A(t) + X(t)$, $X(t) = m\big(1 - F(t)\big)$ and $A(t) = mF(t)$.

The proposed model consists of three coupled Bass models, each with their own innovation and imitation

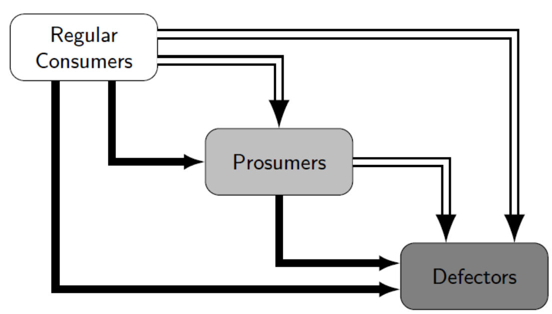

Figure 3. Stock & Flow diagram of the relationship between consumption types

[DOI: 10.61186/joc.17.3.37]

paths, as depicted in Fig. 3. In this diagram, solid and hollow arrows indicate adoption through imitation and innovation, respectively. It is important to notice the possibility of regular consumers to directly become defectors by either imitation or innovation. Also, we assumed that the transitions are one-way, meaning that once a customer installs PV or batteries, they won't disconnect them.

The transition of customers between consumption types is determined by the coefficients of innovation and imitation from (2), which are chiefly influenced by the financial viability of each energy system represented by Net Present Value (NPV) and discussed in Section V. Since the NPV values could rise substantially during the simulation, the coefficients should be limited to keep them in reasonable and realistic levels. For this purpose, the coefficient for each transition is the result of multiplying a base value and the attractiveness of the transition, which is modeled by logistic (sigmoid) function which acts as a limiting factor as used in [15]. The logistic function is formulated as (3) and depicted in Fig. 4:

$$e(t) = b + \frac{L}{1 + e^{-k(x(t)-x_0)}} \qquad (3)$$

The input of $e(t)$ is the Net Present Value (NPV) of becoming a prosumer or defector. b, L, k, and x_0 are function parameters that adjust the shape for each route based on its characteristics. In this paper, innovators are assumed to be attracted with lower NPV values meaning that x_0 is smaller compared to that of imitators. Also, the share of each consumption type from new customers is determined based on their corresponding attractiveness.

B. Price Elasticity

In addition to installing DERs and becoming prosumers or defectors, another path for customers to respond to price increases is through reducing their base demand which is known as price elasticity of demand in economics literature.

To model this aspect of customers behavior, an average monthly electricity consumption is assumed for each consumer type (Defectors are not included since they are disconnected from the grid) which is adjusted every time the electricity tariff changes based on the equation for price elasticity of demand:

$$\epsilon = \frac{\frac{\Delta D}{D}}{\frac{\Delta P_e}{P_e}} = \frac{P_e}{D}\frac{\Delta D}{\Delta P_e} \quad \Rightarrow \quad \Delta D = \epsilon \frac{D}{P_e}\Delta P_e \qquad (4)$$

where ϵ is the price elasticity of demand, which is negative for electricity, P_e stands for the price of electricity and D represents demand.

We have assumed that the price elasticity for prosumers is higher than regular consumers since they have onsite generation and are typically more proactive and responsive to utility actions. Additionally, the range of demand change due to price elasticity is limited in the model to 20% of the initial value.

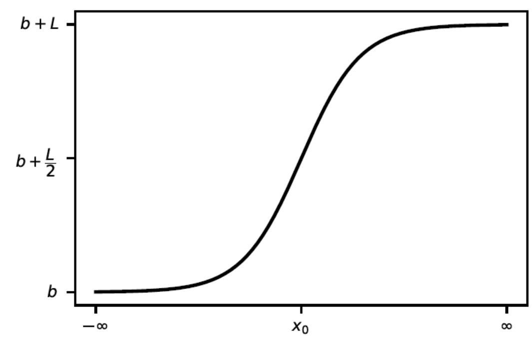

Figure 4. Logistic function $e(t)$

IV. UTILITY BUSINESS MODEL

The utility is considered to be a regulated monopoly and is allowed to gain a fixed profit. Hence, the electricity price reflects utilities costs plus the permitted profit and is calculated accordingly. Although there are other factors that influence electricity retail tariffs such as governmental subsidies or political considerations, they are excluded from this study in order to focus on the effect of utilities financial performance on tariff evolution.

A. Utility Costs

Utility costs include the fixed costs, which are independent of utility sales, and variable costs that mainly reflect energy provision costs and directly depend on the demand.

$$C_{tot} = C_{fix} + G\pi_g = C_{fix} + Sale(1 + loss)\pi_g \qquad (5)$$

where C_{tot} and C_{fix} stand for total and fixed costs, respectively. π_g is the price of providing 1 kWh electricity and G represents the total energy that the utility should procure, which includes total sales to customers plus network losses. For the sake of simplicity, we have assumed that fixed costs and generation price would remain constant during the study period. Note that the proposed model is indifferent to the utility's structure. It is clear that when utility sales drop, fixed costs would remain unchanged while variables costs decline proportionally. This is the main driver of the "Death Spiral" as the average cost to be recovered by each consumer has an opposite relationship with sales.

Utility Sales is the total energy sold to prosumers and regular consumers as stated in (6):

$$Sale = N_p D_p + N_r D_r \qquad (6)$$

In this equation, N and D stand for Number and average

[DOI: 10.61186/joc.17.3.37]

demand of each consumption type, while the subscripts p and r denote prosumers and regular consumers, respectively. It is also important to mention that while we are focused on the residential sector in this study, there are increasing number of industrial and commercial customers in developed countries who have already started or have plans to become more self-sufficient and eventually net-zero energy in the future. Therefore, the generality of the model is guaranteed.

B. Revenue

It is assumed that all customers are billed with a constant volumetric tariff for their total monthly consumption. The actual utility revenue can thus be expressed as the product of total demand by electricity tariff:

$$R_{act} = Sale \cdot P_e \tag{7}$$

C. Price

Theoretically, with few simplifications, the electricity tariff issued to consumers would be calculated by dividing the expected revenue by total sales, as follows:

$$P_e = \frac{R_{exp}}{Sale} = \frac{C_{tot}(1 + profit)}{Sale} \tag{8}$$

The logic behind (8) assumes immediate correction of retail tariff, following any change in utility sales. However, since tariff changes should pass through local regulation board, it is always actualized after a time delay.

In this paper, we propose a new approach to model price revisions which is depicted in Fig. 5 as a stock & flow diagram. It is assumed that the electricity tariff is revised in fixed time intervals to simulate regulatory and corporate delays. During this period, any mismatch between the utility's expected and actual revenue is

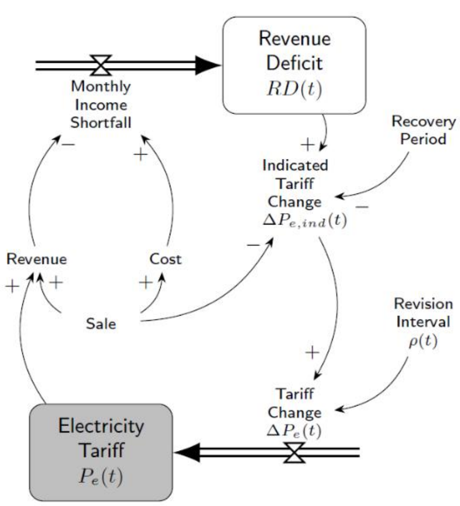

Figure 5. Stock & Flow diagram of the proposed tariff revision mechanism

accumulated as revenue deficit $RD(t)$ as formulated in

$$RD(t) = \int Shortfall = \int (R_{exp} - R_{act}) \tag{9}$$

When the time of price revision comes, it will be set in a way that the utility recovers its revenue deficit in a reasonable time. Therefore, assuming everything remain constant, the required change in electricity tariff $\Delta P_{e,ind}(t)$ which recovers utilities revenue deficit could be calculated by:

$$\Delta P_{e,ind}(t) = \frac{RD(t)}{Sale(t) \cdot T_{rec}} \tag{10}$$

In this equation, T_{rec} represents the time period during which the utility intends to recover its lost revenue. Since $\Delta P_{e,ind}(t)$ should only be added to the electricity tariff P_e in predefined time intervals of revision, we multiply it by the revision interval function $\rho(t,i)$ which is always zero, except at the time of price revision. Ultimately, the mechanism for price revision based on Fig. 5 is formulated in (11).

$$P_e(t) = \int \Delta P_e(t) = \int \Delta P_{e,ind}(t) \rho(t,i) dt + P_{e,0} \tag{11}$$

V. DER Model

Since the role of DERs is intrinsically different for prosumers and defectors, two separate models are developed for each of them. Prosumers use both PV panels and utilities grid, even selling excess electricity generated from PVs to the grid, which means that the grid is essentially playing the role of a lossless and infinite energy storage for them. On the other hand, defectors are completely disconnected from the grid and therefore typically install more PV panels alongside storage systems to meet their electricity demand.

We have developed models to simulate the price evolution of PV panels and batteries since they are the principal components of DERs. Their output is then fed into prosumers and defectors financial models which subsequently affect the flow rates of customers between concepts.

A. PV

The Price of PV panels is affected by two factors:

- The normal decline rate of global prices as a result of technology development,
- Size of the local PV market. It has been stated in several articles that due to the immaturity and novelty of the PV market in many regions, the price of PV systems tends to drop with increasing local installations [16], [17], [19].

Since both the above factors push the PV price to decline, a minimum price for PVs is included in the model to prevent it from reaching unrealistic levels. The output of

[DOI: 10.61186/joc.17.3.37]

this submodel is the price of PV panels which is used to calculate the financial performance of prosumers and defectors compared to regular consumers.

B. Battery

The Battery cost model is similar to PV. There is a normal cost reduction rate exogenous to the model, in addition to the local market size effect that accelerates price reduction. Similarly, a constraint on the minimum battery cost is also included in the model. The output of battery submodel is the unit cost of batteries used in the stand-alone system by defectors.

Note that the number of customers who have already installed batteries is vastly different from the number of customers with PV panels, as the former consists solely of defectors, while the latter also includes prosumers. As a result, the effect of market size on price reduction is quite different between batteries and PVs.

C. Prosumage

Customers are assumed to use Net Present Value (NPV) for economic evaluation of acquiring each consumption type. The NPV of a PV system for prosumers is calculated as follows:

$$NPV_{pv} = \left(NPV_{I,pv} - P_{pv}\right) \cdot N_{pv} \quad (12)$$

In this equation, N_{pv} stands for the size of PV system in kWs and is constant, P_{pv} is the price of a unit (1kW) PV and $NPV_{I,pv}$ represents the net present value of the total income that a unit of PV generates in its lifetime, which is calculated according to:

$$NPV_{I,pv} = \sum_{t=1}^{T_{pv}} \frac{I_{pv,m}}{(1+i)^t} = I_{pv,m}\frac{(1+i)^{T_{pv}+1}-1}{i} \quad (13)$$

where T_{pv} is the lifetime of the PV system in months, i is the discount/interest rate and $I_{pv,m}$ is the monthly income of a unit of PV calculated as the product of monthly energy generation of a unit PV ($Gen_{pv,m}$) by the electricity retail tariff:

$$I_{pv,m} = P_e \cdot Gen_{pv,m} \quad (14)$$

The equation (14) implies that prosumers are billed by net-metering, because all the energy produced by the PV system is purchased at retail tariff. The NPV of installing PV is calculated in each time step using the latest electricity price.

D. Grid Defection

The model for defectors is more complex, compared to that of prosumers, as their system size should be determined to meet all their electricity requirements. Sizing of the system consists of determining the size of PV generation subsystem and the battery energy storage size. The number of PVs in the stand-alone system is calculated as:

$$N_{pv} = \left\lfloor \frac{D_r(1+M_{rel})}{Gen_{pv,m}} \right\rfloor + 1 \quad (15)$$

In this equation D_r represents monthly electricity demand of the consumer, and $\lfloor\cdot\rfloor$ means rounding the decimal number down to the nearest integer. Since the defector would completely rely on the PV and battery system to meet its entire electricity demand, the number of PVs should be higher than what merely meets their monthly energy requirements. Thus, a reliability margin M_{rel} is considered in calculating the number of PVs to account for system losses and uncertainties of PV generation.

The number of batteries can be calculated similarly. However, as the role of batteries is to compensate for the mismatch of PVs outputs and consumer demand during the day, their number is a function of daily consumption parameters:

$$N_b = \left\lfloor \frac{D_r}{30}\alpha_d \right\rfloor + 1 \quad (16)$$

where α_d is the portion of daily demand that should be supplied from the batteries, mostly at night.

Using the result of (15) and (16), the cost of installing a stand-alone system is then calculated using equation:

$$Cost_d = N_{pv}P_{pv} + N_bP_b\left\lceil \frac{T_{pv}}{T_b} \right\rceil \quad (17)$$

The second term in the right-hand side of (17) models the shorter lifetime of batteries, compared to PVs, and the cost of replacing them several times during the life of the system. Also, $\lceil\cdot\rceil$ means rounding the decimal number up to the nearest integer. The net present value of defection can be calculated by $NPV_d = R_d - Cost_d$, where R_d stands for the net present value of defectors' savings from not paying for electricity demand. It is the sum of monthly avoided costs (P_eD_r) over the life of the system, assuming electricity tariff stays the same, and is calculated using:

$$R_d = \sum_{t=1}^{T_{pv}} \frac{P_eD_r}{(1+i)^t} = P_eD_r\frac{(1+i)^{T_{pv}+1}-1}{i} \quad (18)$$

It is important to point out that NPV_d is only applicable when a regular consumer directly installs a stand-alone system. If a prosumer decides to install additional PV and batteries to become a defector, the NPV of such transition would be calculated as $NPV_{p\to d} = NPV_d - NPV_{pv}$.

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VI. CASE STUDY

The model is structured using Vensim PLE and simulated using Python PySD package for 240 months to analyze the results. First, the model response to standard input data is presented and discussed. After that, sensitivity of the model responses to selected parameters will be analyzed.

A. Data

The input data of the model are obtained from various sources and presented in Tables I, II and III. Latest renewable data reported in [49] are used for PV and battery initial costs and decline rates. Additionally, customers and utility data are derived from Edison Energy yearly financial report [50]. The study by Quoilin et al. [51] finds that a 5kW PV system without battery can result in about 45 percent self-sufficiency. Therefore, we have assumed that prosumers consume 275 kWh per month compared to 500 kWh per month for regular consumers. The latest average population growth rate for OECD countries based on the latest data [52] is 0.4% per year which we used in this study. Price elasticity of demand for regular consumers is assumed to be -0.1 as reported by Burke and Abayasekara [53] and -0.2 for prosumers [54].

B. Base Case Simulation

In order to establish a basis for comparison, the model is first simulated using the input data presented in Tables I, II and III. Although the proposed model consists of numerous variables, a few of them that better represent the financial impact of DERs are analyzed in this section, such as electricity retail tariff and utilities revenue deficit. Fig. 6 and Fig. 7 show the evolution of electricity retail tariff and utility sales respectively.

The electricity price rises sharply initially but starts to decline slowly with oscillation (Fig. 6). In parallel, utility sale drops 15% from its initial value in the same period (Fig.7). This is because the fraction of PV consumers (prosumers and defectors) reaches its peak (30 percent of the households) around the third year as can be seen in Fig. 8. After this point, the share of regular customers remains mostly unchanged, meaning that their number increases with population growth (Fig. 9) but since there is no room for new PV installation, prosumers gradually become defectors and their populations drops as evident

Table I
UTILITY BUSINESS DATA

Parameter	Value	Unit
Generation Price	0.06	Dollar/kWh
Fixed Costs	140	Million Dollar/Month
Permitted Profit	15	%
Electricity Loss	10	%
Initial Revenue Deficit	0	Dollar
Initial Electricity Tariff	0.15	Dollar/kWh
Tariff Correction Period	12	Months
Deficit recovery period	6	Months

Table II
CUSTOMER DATA

Parameter	Value	Unit
population growth rate	0.4	%/Year
New Defector Ratio	0.1	Dollar
Innovation factor	1	%/Year
Imitation Factor	2	%/Year
PV visibility effect on imitation	3	-
Initial Demand (Consumers)	500	kWh/Customer/Month
Consumers Price Elasticity	-0.1	-
Initial Prosumer Demand	275	kWh/Customer/Month
Prosumers Price Elasticity	-0.2	-
Demand Change Limit	20	%
Demand Adjust Time	3	Month

Table III
DER DATA

Parameter	Value	Unit
Battery Life	40	Month
Discount Rate	1.2	%/Year
Initial Battery Cost	600	Dollar/kWh
Initial PV Cost	4000	Dollar/kW
Minimum Battery Cost	100	Dollar/kW
Minimum PV Cost	100	Dollar/kW
Normal Battery Cost Reduction rate	0.006	%/Month
Normal PV Cost Reduction rate	0.01	%/Month
PV Life	240	Month
PV Potential	30	%
PV monthly Generation	140	kWh/Month
PV size	5	kW
Reliability Margin	50	%
Storage to Daily Load Factor	50	%

[DOI: 10.61186/joc.17.3.37]

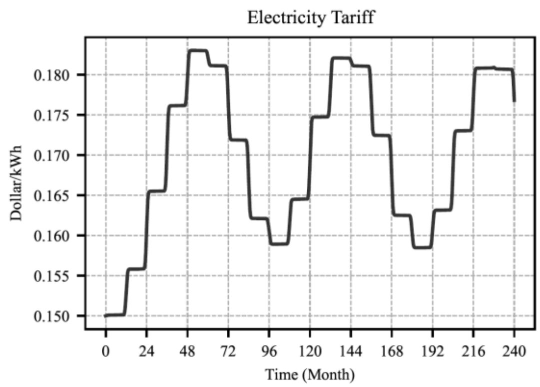

Figure 6. Base Case - Electricity tariff evolution over time

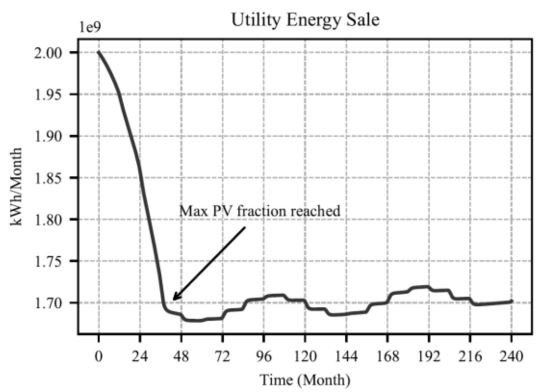

Figure 7. Base Case - Total monthly energy sale

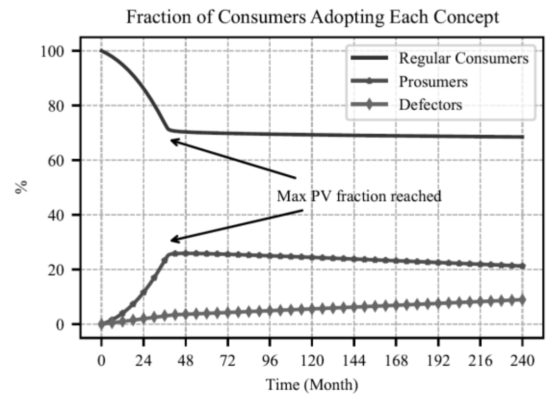

Figure 8. Base Case - Fraction of each consumption type

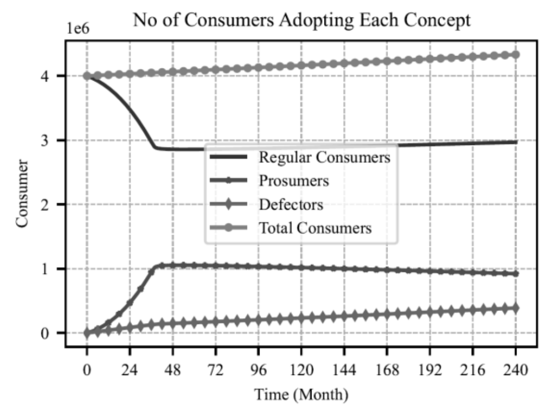

Figure 9. Base Case - Population of each consumption type

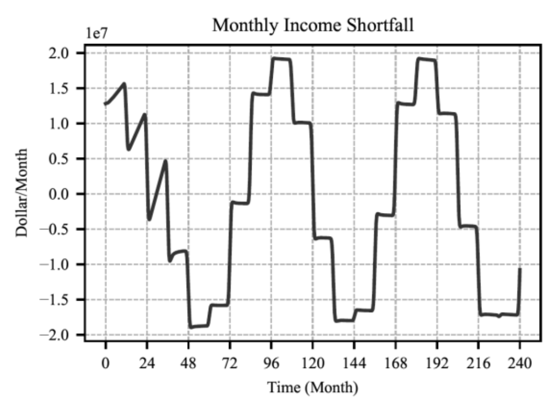

Figure 10. Base Case - Utility monthly income shortfall

in figures 8 and 9. Although only 30 percent of all customers can install DERs, utility energy sale suffers a heavy loss during the study period and remain at 30% below initial levels. It is obvious from the figures that the population growth cannot compensate for the lost customers.

The Utility offers new tariffs to restore the balance between its cost and revenue as described in Section IV. Fig. 10 shows income shortfall of the utility which represents the difference between its income and costs. The shortfall starts positive and slowly declines as the price increases (Fig. 6). The delay in the price adjustment causes an overshoot which not only diminishes revenue deficit (Fig. 11) but also generates excess income. Since regulations prohibit the utility to gain more profit than permitted, the price should be reduced once the revenue deficit becomes negative. This causes the fluctuating pattern in the electricity tariff which subsequently manifests itself in monthly income shortfall and revenue deficit.

The base case results suggest that the death spiral is unlikely to happen, given the conditions described by the data. Although population growth cannot compensate the lost sale of the utility, its revenue deficit barely matches monthly total costs (Fig. 12) which is not enough to substantially impact utility business model. Besides, electricity retail tariff rises merely 20 percent in 4 years, only to be gradually damped with oscillation, in the following years. However, simulation results show an interesting oscillation pattern, that can be explained by the structure of the model and the delay in the price revision process. In the following section, we analyze this behavior through sensitivity analysis. It is worth noting that, this oscillation behavior is similar to the boom-and-

[DOI: 10.61186/joc.17.3.37]

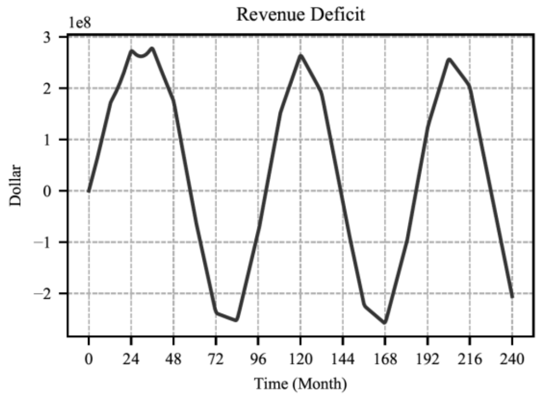

Figure 11. Base Case - Utility revenue deficit

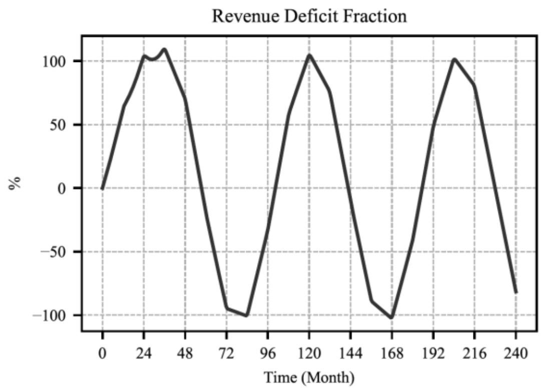

Figure 12. Base Case - Utility revenue deficit as a percentage of total costs

bust cycles in power plant construction in early years of 21st century in California [55].

C. *Sensitivity Analysis - Tariff Correction Period*

As stated before, the process of implementing new electricity tariff takes time and is usually performed in fixed time intervals. The proposed model captures this process. The default value for the interval between tariff revision is considered 12 months as it coincides with fiscal year. We have simulated the model for several values between 1 and 36 months, in order to analyze its effect on model response. Fig. 13 shows that the amplitude of tariff oscillation increases with larger time intervals, while the frequency has a reverse relation. This is expected, since the mismatch between expected and actual revenue is balanced more quickly, and would be less accumulated, as a result of the more frequent tariff revision, which is evident in Fig. 14. It can be seen in this figure that maximum revenue deficit for period revision of 36 months is almost 8 times higher comparing to that of 1 month.

However, results suggest that utility sales do not change significantly by electricity tariff revision period (Fig. 15). This is due to the fact that similar to base case; the range of price change is not large enough to affect the net present value of installing PV and storage significantly.

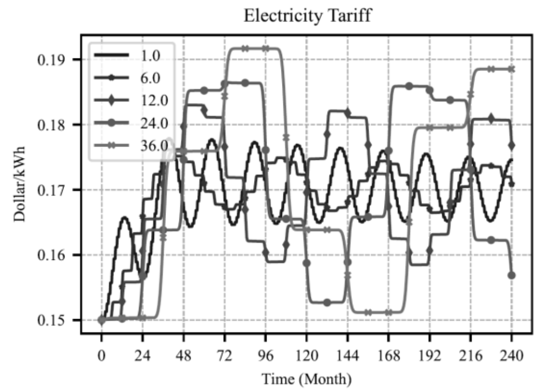

Figure 13. Sensitivity Analysis - Effect of Tariff Adjustment Interval on price over time

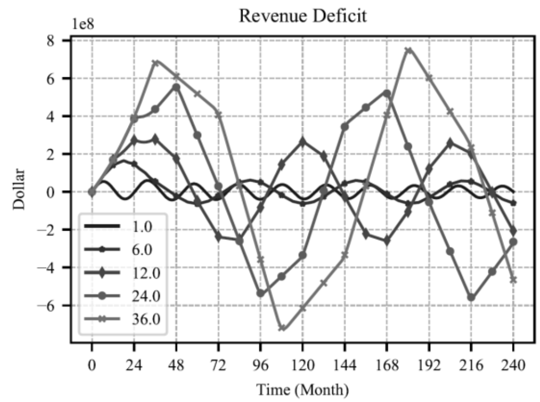

Figure 14. Sensitivity Analysis - Effect of Tariff Adjustment Interval on revenue deficit over time

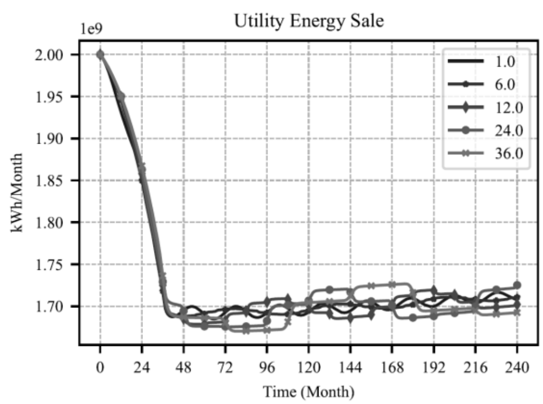

Figure 15. Sensitivity Analysis - Effect of Tariff Adjustment Interval on utility energy sale over time

As a result, the share of each consumption concept and consequently, the utility sales, are practically untouched. With increasing revenue deficit and constant sales, the burden of income shortfall will increase significantly for the utility. Fig. 16 shows that if the price is revised every three years, the monthly revenue deficit could rise to 300 percent.

As stated above, longer price revision intervals increase

[DOI: 10.61186/joc.17.3.37]

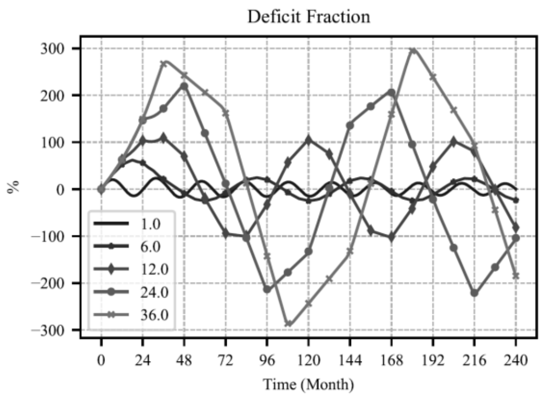

Figure 16. Sensitivity Analysis - Effect of Tariff Adjustment Interval on revenue deficit percentage of utility's total costs

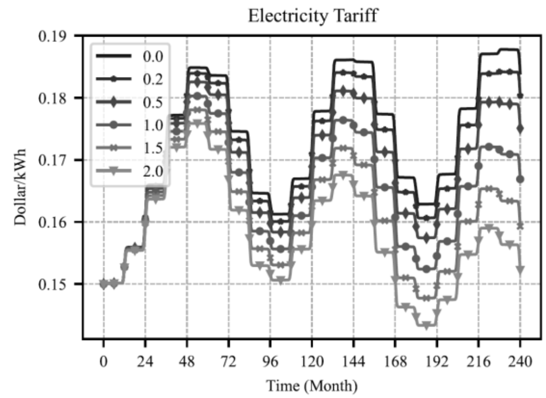

Figure 17. Sensitivity Analysis - Effect of Population growth rate on electricity tariff over time

financial pressure on utilities and result in higher price levels for the customers. Therefore, it seems that increasing the agility of utilities and regulation bodies in order to react more quickly to changing conditions can benefit both the electric power industry and its users. However, by decreasing the frequency of price revisions, the system would be faced with more frequent albeit less strong fluctuations. The effect of these fluctuations can be the subject of future studies on the impact of distributed generations on power system and more specifically, death spiral.

D. Sensitivity Analysis - Population Growth

Base case simulation results, with relatively low population growth rate, showed that after the regional PV potential is exploited completely, population growth restores some of the utility lost sales. Therefore, the effect of population growth rate on the results is investigated henceforth. We simulated the model with a range of growth rates from 0 to 2% per year and the results are presented hereafter.

As expected, population growth directly affects the simulation results. Electricity tariff drops in response to increased population as shown in Fig. 17. It can be seen in Fig. 18 that utility sales also bounce back when the population increases fast enough. On the other hand, it seems that for low growth rate of below 0.2% per year, the magnitude of tariff fluctuations increases over time and utility sales continue to drop, even after the PV potential has been fully exploited. This signals to the risk of collapse in the utilities business model for low growth economies.

Additionally, since the utilities costs and sales rise at the same time (Figs. 18 and 19), the population growth doesn't compensate utilities financial burden due to the loss of customers. This can be observed in Figs. 20 and 21 as the revenue deficit and its ratio over total costs remains essentially constant for the range of simulated population growth rates.

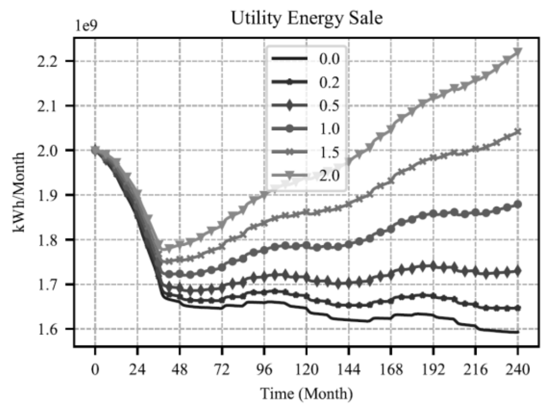

Figure 18. Sensitivity Analysis - Effect of Population growth rate on utility's energy sale over time

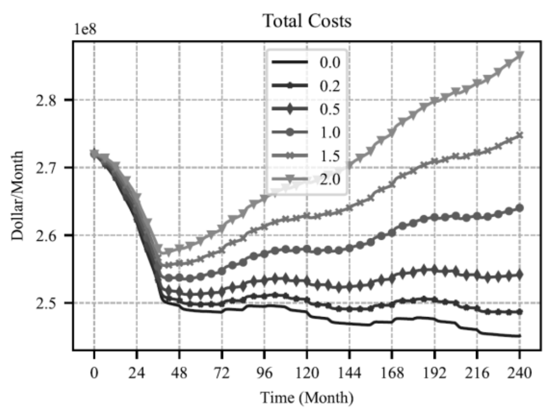

Figure 19. Sensitivity Analysis - Effect of Population growth rate on utility's total costs over time

The simulations in this section point to the significant impact of population growth on the electricity tariff. It is evident in the results that even if the utility can restore its sales through new customers, the fluctuations in its revenue deficit will remain untouched. In other words, population growth can prevent severe loss of customers and sales for utilities, but the fluctuations in revenue and deficit cannot be avoided because they are the natural

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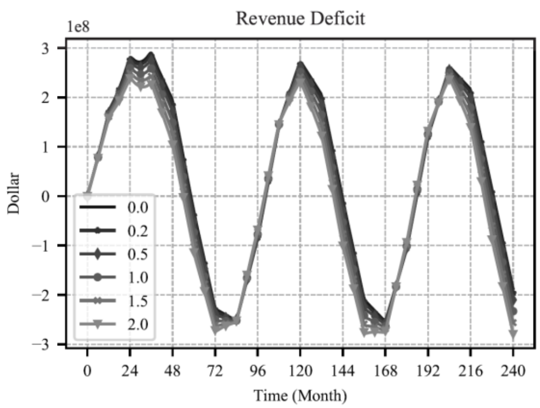

Figure 20. Sensitivity Analysis - Effect of Population growth rate on revenue deficit over time

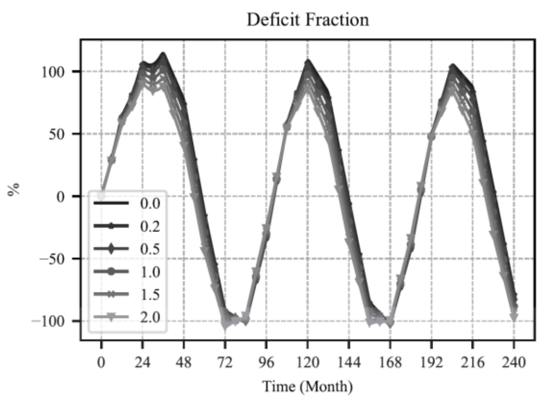

Figure 21. Sensitivity Analysis - Effect of Population growth rate on revenue deficit percentage of total utility's costs

consequence of system delays.

VII. Conclusion

With the rising environmental concerns and constant drop in PV and battery prices, it is now clear that the electric power industry is going through a substantial change. There is an ongoing debate about the effect of high renewable penetration levels on the power system from various aspects. The feasibility of current utility business model in the face of widespread use of distributed energy resources is one of them.

In this paper, we seek to evaluate the effect of DERs, specifically rooftop solar PVs, on the financial performance of a regulated utility. The interaction between electric utilities, distributed energy resources and consumers have been modeled comprehensively using System Dynamics (SD). Three types of consumers were included, and Bass model was used to describe transition between them. Furthermore, population growth and the limitations of using rooftop solar in cities has been included in the proposed model. We have also incorporated the price elasticity of customers in the model as a parallel route for them to respond to price changes. Our model captures important time delays in the system, such as price revision delay and customers response time that had been neglected in previous studies. Most importantly, a new mechanism for electricity tariff revision is proposed, which better reflects the real-world process.

The model is simulated using real world data and its sensitivity to several key parameters has been analyzed. We found that although DERs can significantly reduce utility sales, but with current conditions, they are unlikely to cause a threat to the utilities business model as price increases compensate for their lost customers. However, simulations also presented a unique and remarkable oscillation pattern in key variables of the model as a result of the new price revision process. We witnessed that the delay between subsequent price changes causes an unbalance between the utilities expected and actual income, which, coupled with inaccurate predictions, creates fluctuations in electricity tariff.

Our sensitivity analysis highlighted the important role of the tariff revision period. We found that if the interval between subsequent price revisions is shortened, not only the financial impact of the DERs on utilities could be mitigated, but also customers experience more reasonable price increases, although with more frequencies. This points to the importance of improving the response time of utilities and regulators in order to prevent the death spiral from gaining traction. Additionally, population growth proved to be a significant influencing factor. If the population growth is near zero, the risk of death spiral is undeniable. On the other hand, higher growth rates can compensate for the loss of customers and sales, although they cannot prevent the fluctuation in utility's revenue deficit.

This study shows that the combination of low population growth and slow regulatory process can lead to a death spiral. However, even if the death spiral is not an immediate threat to a utility, price and revenue fluctuations due to widespread use of DERs and regulatory delays should be something to look out for.

The research reported in this article can further be enhanced by integrating different pricing schemes. Additionally, the effect of this phenomenon is not yet assessed on a wholesale power market and independent power producers.

Appendix

A. *Brief introduction to system dynamics*

System dynamics (SD) is a technique for modeling complex and interrelated nonlinear systems, introduced by Prof. J. W. Forrester of Massachusetts Institute of Technology (MIT) in the 1950s. Its main advantage over

[DOI: 10.61186/joc.17.3.37]

competing approaches is modeling the feedback loops between system parameters and their interaction over time. A system dynamic model is a set of discrete differential equations linking different variables together and the system's future state to its current state. SD models are mainly presented in two forms: 1-Causal Loop Diagrams (CLDs) and 2-Stock & Flow Diagrams.

A CLD shows the causal relationship between variables and is used to identify the feedback loops and their polarity in the system. An example of a CLD is shown in figure 22. The variables in the system presented in this diagram are population, birth rate, and death rate. Additionally, fractional birth rate and average lifetime are exogenous parameters since they are not directly affected by the variables. However, if we expand the system's borders, they can also become system variables. The arrows show the relationship between two variables, and the sign represents the polarity of the effect. In this system, we can observe that the arrow linking the population to the death rate is marked positive, meaning that if the population increases, the death rate will also increase. On the other hand, the negative polarity of the arrow linking the death rate back to the population means that if the death rate rises, the population will decline. Another feature of CLDs is the manifestation of feedback loops in the system. In the system presented in fig. 22, there are two feedback loops. There is a reinforcing feedback loop (positive feedback) between population and birth rate, which is marked with a small R loop symbol. Additionally, a balancing feedback loop (negative feedback) between population and death rate is formed, which is marked with a small B loop symbol.

Stock & flow diagrams are a more detailed representation of an SD model. In an SD model. Variables are either stock or flow. Stocks are the state of the system and represent accumulation. Flows are the rates of changes in stocks. The stock & flow representation of the population growth system depicted as CLD in fig 22 is shown in fig 23. In this diagram, the birth rate is the inflow to the population, and the death rate is the outflow. A stock can have numerous flows. The hollow arrows connecting flows to the stock represent material flow, which in this case, are the individuals. The thin arrows that end in the flows are information flows. Based on the diagram in fig 23, population and birth rate are formulated in equations (A.1) and (A.2), respectively. Further information about System Dynamics can be found in [13].

$$\text{Population}(t) = \int_0^t (Birth\ Rate - Death\ Rate)\,dt \quad \text{(A.1)}$$

$$Birth\ rate(t) = Population(t) \times Fractionl\ Birth\ rate \quad \text{(A.2)}$$

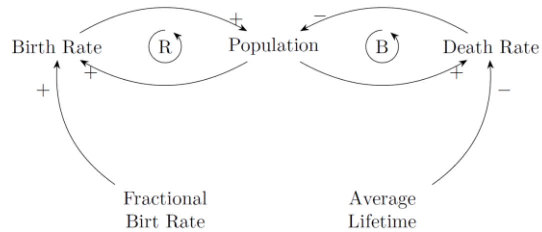

Figure 22. Causal Loop Diagram (CLD) of a simplified population model

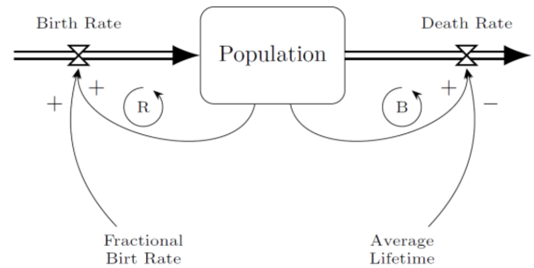

Figure 23. Stock & Flow Diagram of a simplified population model

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[DOI: 10.61186/joc.17.3.37]