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Myths and facts of the utility death spiral

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ABSTRACT

As the electricity industry is changing worldwide, the swift expansion of basic forms of Distributed Generation (DG), particularly photovoltaic deployment, threatens the current utility business models that during the transitional stages may challenge the reliability of electricity systems and societal welfare. These findings are matters of major concern to policy makers as the shift towards more decentralized power systems must be sustainable, and although this brings great opportunities, it also pauses important challenges. The transition calls for policy and regulation attention. For some researchers, DG development should be accompanied with design changes to distribution tariffs, the addition of connection charge and modifications to Net Metering, while for others, certain of these measures could discourage DG investments. In this context and given multiple uncertainties, the authors propose a system dynamics model to examine the effect of the diffusion of Photovoltaic technology on the revenues of utilities and customers. The paper concludes that for the Colombian case, it is possible under certain conditions to attain a balance between social welfare and the aversion of the utility death spiral through systemic interventions.

1. Introduction

With the current diffusion of renewables in power systems, energy policy seeks to balance three conflicting targets: system reliability, environmental quality and consumer affordability. Although none of these have been disregarded, in the industrialized world, the one that has received most attention is CO_2 emissions in electricity productions, as Green House Gases (GHGs) affect human life on earth (Boston, 2013; Eyraud et al., 2013; World Energy Council, 2013).

In power systems, largely the greatest emitter of all sectors (OECD/IEA, 2016), decarbonisation can be attained through technology conversion from fossil - towards renewables-based generation. This will in turn have an effect on a number of variables, particularly on reductions in both spot prices and sales of incumbent utilities, as renewables displace more expensive technologies from the merit-order dispatch of energy (Cludius et al., 2013; O'Mahoney and Denny, 2011), prompting declines in revenues and profits of the incumbent utilities (Costello and Hemphill, 2014; Bronski et al., 2014; EPRI, 2014; Satchwell et al., 2015a).

In this context, the *death spiral of utilities* may occur (Castaneda et al., 2017), as the greater ratio between the electricity tariff and the cost of solar PV sparks the adoption of solar PV panels by households. Note that the transportation cost of electricity from the grid – transmission and distribution – is largely fixed and is recovered through charges allocated to customers; these are volumetric, i.e., they can be calculated as the fixed cost divided by the electricity demand (Hledik, 2014). With more PV systems in place, electricity demand falls, which forces utilities to raise charges in order to compensate for energy usage reduction and to help recover costs; the rise in retail rate accelerates PV adoption and further charge increases, inducing a utility death spiral as described in Fig. 1 by reinforcing loops R2 and R3. This, combined with the learning-curve effects, leads to a higher ratio between the electricity tariff and the cost of solar PV, incentivizing PV adoption (see reinforcing loop R1 in Fig. 1).

Although theoretically feasible, others argue that the utility death spiral is unlikely as this implies an unreasonable inertia from utilities and regulators (Eid et al., 2014; Costello and Hemphill, 2014); nonetheless, it is a threat to the incumbent distribution utility and to societal welfare (Clift, 2007; Hirschberg et al., 2004). The move towards a decentralized power industry requires appropriate transitional attention, considering technical, economic and institutional implications (EC, 2015; IEA, 2016).

Given the current energy transformation that is taking place worldwide, this paper explores policy changes that could lead to a more

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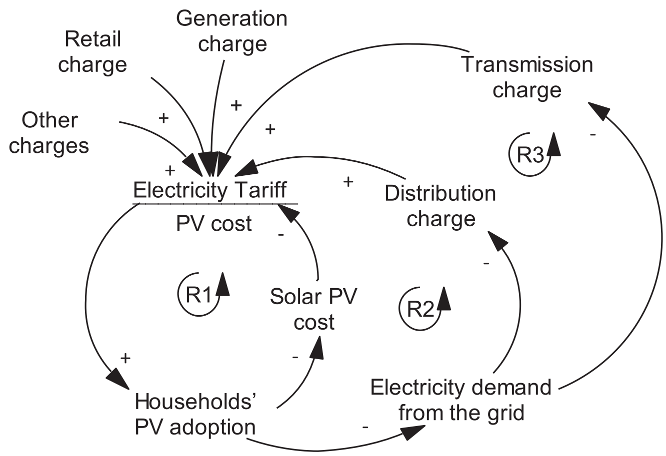

Fig. 1. Systems thinking consideration of the utility death spiral. Source: Own elaboration.

sustainable energy paradigm, considering the economic implications on utilities and customers. This paper does not advocate the protection of traditional utility business model; on the contrary, it studies feasible alternatives for a sustainable transition by reducing the negative effects for society, considering the two main stakeholders, customers and suppliers.

Given the multiplicity of possible solutions to the negative effects brought by the abrupt collapse of utilities, the main objective of this research is to identify some of the determinants of a utility death spiral, and some of the likely policy alternatives to confront the transition process under a systemic and sustainable perspective. This paper therefore explicitly addresses some important research questions regarding the death spiral issue, including the following: What are the market conditions that may lead to a death spiral for utilities? What can the regulator and utilities do to avert a death spiral achieving social welfare? Can simulation be of any help to support corrective actions that benefit the technology transition?

To answer the above questions this paper presents a system dynamics (SD) model to assess the financial impact of solar PV development on utilities and customers. The case study is the Colombian electricity market, due partly to its great potential in solar PV energy resources, and mostly because of its commitments to reduce 20% of greenhouse gases emissions by 2030 (Ministerio de Medio Ambiente, 2015).

This research chooses the SD approach over other methodologies, given the nonlinearities and predictive complexities involved. SD is particularly suitable for capturing the dynamics of markets and feedbacks e.g. solar PV cost, transmission and distribution charges. Given the difficulty of predicting solar PV penetration, this approach offers an attractive way of understanding how markets might evolve, for instance by generating insights into how solar PV penetration may affect utilities (Dyner and Larsen, 2001; Ponzo et al., 2011).

The paper is organized as follows. **Section 2** provides an overview of the literature on the penetration of distributed generation (DG), with emphasis on the death spiral problem, the focus of this paper. **Section 3** describes an SD model that has been built to study the dynamics of the current electricity market in Colombia. **Section 4** discusses the simulation results and policy analysis, and finally, the study's conclusions are presented in **Section 5**.

2. Utility death spiral issue

The increasing diffusion of distributed solar generation has inspired a broad spectrum of research of its effect on power markets and energy policy. This section aims at addressing the research questions posed earlier by reviewing the existing literature. Thus, studies were categorized according to following issues: the market conditions that may lead to a death spiral for utilities; the policies that may avert the negative impacts of a high penetration of DG or death spiral–if it were possible; and finally, the modelling approaches that have been used to assess the extent of these impacts.

2.1. Market conditions to a death spiral

The market conditions that may lead to the utility death spiral were identified by Costello and Hemphill (2014), who present a quantitative analysis of the necessary economic and regulatory conditions for the utility death spiral; although possible, the paper argues that it is unlikely as it would assume an inert attitude from utilities and regulators.

Others have studied the effects of distributed solar generation on both customers and utilities under different market conditions. For example, Darghouth et al. (2011) estimated the bill savings obtained by residential and commercial PV customers under different compensation mechanisms for distributed PV and tariff designs; they found that Net Metering regulation (which offsets households' electricity consumption from the grid during the evenings against their electricity surpluses during the day, yielding the net energy consumed or dispatched (Comello and Reichelstein, 2017; Geffert and Strunk, 2017) provides significantly greater bill savings in comparison with other compensation mechanisms. Oliva et al. (2016) study the short-term financial impacts of the penetration of PV systems on the different agents involved in the electricity sector of New South Wales, Australia. For this, they considered different compensation mechanisms: gross and net PV feed-in tariffs; and different retail tariff arrangements: block and time-of-use retail electricity tariffs. Their findings suggest that the current compensation mechanism, i.e., net PV feed-in tariff, grants moderate revenues to PV adopters, incentivising self-consumption, while causing revenue losses for network service providers and threatening the retail business. Additionally, time-of-use rates may exacerbate these effects on revenue due to the match between shoulder and peak tariff rates with hours of solar output.

Another effect of distributed solar generation on customers is the cross-subsidisation of grid costs between PV adopters and no-adopters (Eid et al., 2014). For instance, Eid et al. (2014) studied the effects of different types of Net Metering methods and tariff designs on Distribution System Operator (DSO) incomes, policy objectives and cross subsidies between network users in Spain. The main conclusion from the study is that Net Metering along with a volumetric charge produce a DSO income-reduction and cross-subsidies; this effect is enlarged with a larger period for which surplus of electricity production is valid.

Finally, Satchwell et al. (2015a) analysed the financial impact of solar PV on utility shareholders and ratepayers. They found that distributed solar generation may reduce the revenue of utilities; however, the electricity tariffs would increase moderately even at the highest levels of PV penetration.

2.2. Policies to avert negative effects of high solar DG penetration

Although Satchwell et al. (2015a) dismiss the possibility of a death spiral, they recognized the revenue erosion of utilities caused by solar DG penetration. In a later study, Satchwell et al. (2015b) use a financial model to quantify the efficacy of different policies for mitigating the financial impacts of solar DG on utilities. Some of these policies have been applied to offset the revenue erosion caused by energy efficiency programs. However, they indicate that these may contribute to the adoption of solar-plus-battery systems, exacerbating the financial problem of utilities.

Other authors that propose changes in tariff designs to avoid cross-subsidisation are Picciariello et al. (2015a), who quantify cross-subsidies from consumers to prosumers by comparing the tariffs of network users and the costs they imposed on the system; these costs are estimated through a Reference Network Model (RNM). They use a

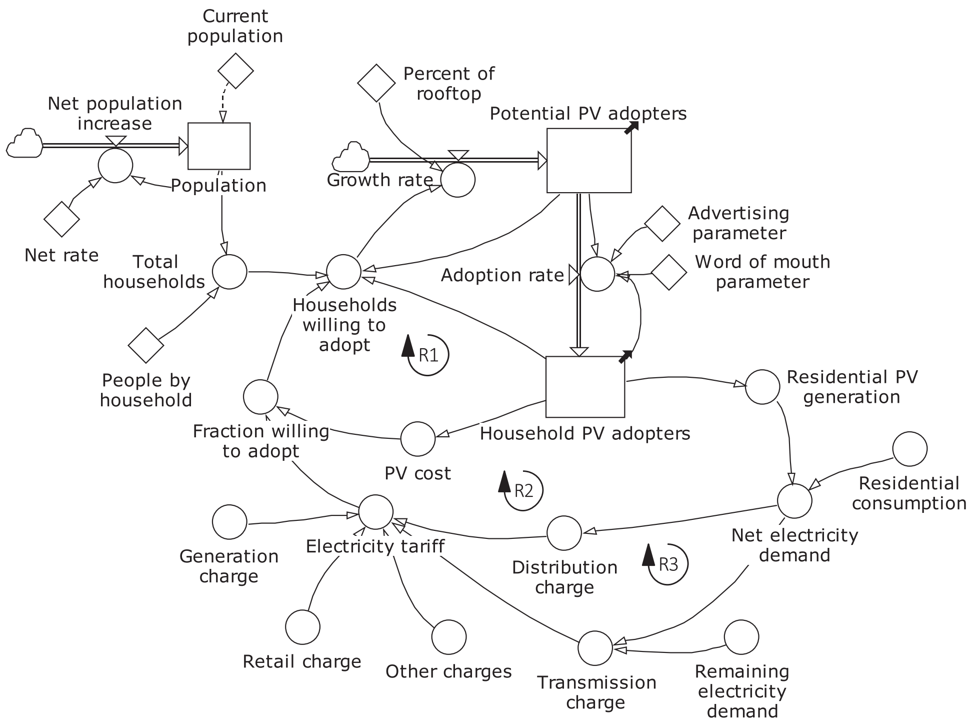

Fig. 2. SD modelling of PV diffusion in the residential sector. Source: Own elaboration.

computational model for conducting 12 simulations of U.S. networks. The results show that cross-subsidies arise when Net Metering and a pure volumetric tariff are applied; therefore, they propose a tariff structure based on the cost-causality principle to better reflect costs based on grid usage.

2.3. Simulation for supporting corrective actions to the technology transition

In contrast to the previous research that does not consider the long-term dynamics associated with PV adoption, other studies, based on modelling approaches, have endogenously incorporated feedback effects between residential PV adoption and electricity rates. For instance, Cai et al. (2013) model endogenously the rate-setting process for capturing the feedback effect of PV adoption on future electricity rates, for an electricity utility in California; they evaluate the impact of this feedback on PV penetration and net metering costs. The findings suggest that feedback reduces the time for PV capacity to reach 15% of demand by approximately four months and could increase net metering costs by 5–10%. In addition, the willingness of customers to adopt PV determines whether this feedback has an important effect.

Darghouth et al. (2016) study two opposite feedback effects for the U.S. case; a positive feedback loop that describes the utility death spiral and a negative feedback loop that results when PV deployment causes a shift in peak-price periods to evening hours, which decreases the benefits of PV adopters – who pay time-varying rates – and therefore damps PV adoption. The authors found that (i) tariff design has an important impact on PV deployment, and (ii) through 2050 the effect of these two feedbacks is to cancel each other; therefore, the aggregate effect on solar PV deployment is modest; in addition, there is no evidence of a death spiral – not even when the positive feedback effect is isolated.

Although modelling has been largely used to assess the impact of PV adoption over the electricity industry, only a few scholars have explicitly used the (SD) approach. For instance, Ford (1997) models the death spiral in the U.S. power industry using SD. This was triggered by the oil embargo in 1973, when utilities, facing financial challenges, asked regulators to raise electricity rates to cover their increased operating and capital costs. Back then, regulators were concerned about the response of utility customers to higher rates, which could lead utilities into a downward spiral.

Grace (2015) develops an SD model for exploring death spiral impacts on DG adoption and storage in Western Australia. The results show that the decrease in solar PV costs drives high solar PV adoption, causing a death spiral, along with benefits for society in terms of lower energy bills. Laws et al. (2016) explores the effects of the residential PV and storage adoption on the retail price of electricity and conclude that pricing structures such as Net Metering reduce grid defection. Castaneda et al. (2017) study the potential impact of renewable energies on electricity systems, specifically on the generation and distribution business, testing the utility death spiral hypothesis from a systems-modelling perspective applied to Colombia, under scenario methodology like the one posed by Smith et al. (2005). Others have also used SD to analyse the effect of different but PV-related issues on power markets (Cardenas et al., 2016; Dyner and Franco, 2004; Franco et al., 2015; Sterman, 2000).

In summary, though there is extensive research that assesses the effects of distributed PV generation on utilities and customers in the short term, little work has focused on policy-related issues to avert the negative consequences of distributed PV generation. Much less work has studied the death spiral issue from a systems perspective, and none has examined it from a systemic intervention perspective in the developing world, under highly hydroelectricity-based conditions, the focus of this paper. Furthermore, this paper studies the dynamic effects between the wholesale power market and the technology diffusion of solar DG. Additionally, unlike Castaneda et al. (2017), the unit of analysis of this paper is the utility electricity industry. This research thus sheds light on the transition towards a more decentralized power sector. An in-depth description of the SD model used in this study is provided in the following section.

3. Model description

This paper discusses next research that no work has to date addressed from an SD approach regarding different systemic interventions for averting the negative effects of the utility death spiral. Fig. 2 presents important components of the SD model that has been built to analyse how different systemic interventions may affect the penetration of renewables and the revenues of utilities. The dynamics of the PV adoption, PV learning curve and rate setting are depicted by a stocks-and-flows diagram. "Households" is the unit of analysis used to measure the potential of PV adopters. PV adoption is considered by household customers with exclusive rights to the rooftop. Potential adopters become PV adopters, through a Bass model, as the adoption rate depends on both social contagious as well as on knowledge about the PV technology. The Bass model describes the adoption of a new product, depending on two forces: the number of previous adopters, and external factors such as price or coverage by advertisements; these influences are parametrized through coefficients (Bass, 1969; Mahajan et al., 1991).

Potential PV adopters increase according to the population growth and new dwellings in place with no PV installations - Households willing to adopt increases by the fraction willing to adopt and population growth. The "fraction willing to adopt" is a function that compares the electricity bill incurred by PV adopters with non-PV adopters – which represents the attractiveness to install PV systems (the variables PV cost and electricity tariff are the main drivers of these energy bills).

The electricity *PV cost* is the levelised cost of generating one kWh from a PV panel. This is calculated as the net present value of total costs (capital and operating costs) divided by the net present value of the energy produced over the economic lifetime of the system. Electricity *Tariff* is the result of accumulating the costs of the electricity supply chain activities – generation, transmission, distribution, commercialization and other charges. As previously mentioned, currently distribution and transmission tariffs are volumetric, which means that they depend on the total energy consumption.

As consequence of the differences between the electricity *PV cost* and the electricity *Tariff*, when electricity PV cost is lower than the electricity tariff, more households will adopt a PV system; conversely, a higher electricity PV cost will reduce PV diffusion. The larger the numbers of *Households that adopt PVs there are,* the greater is the reduction of electricity demand from the grid. The PV adoption is influenced by two different effects: on the one side, *Potential Households* increase or decrease according to the *Households with PV systems* through the Bass model that considers the imitator's population; on the other side, modifications in the *Tariff* result from PV adoption. Finally, revenues of utilities and energy bills for network users depend on the total PV generation by households, the total electricity demand from the grid, the use of the grid and the tariff design.

Table 1 describes the main model equations and their corresponding

Table 1
Main model equations.
Source: Own elaboration.

Equations	Units
$$\textit{Electricity Tariff} = \textit{Generation charge} + \textit{Distribution charge} + \textit{Transmission charge} + \textit{Retail charge} + \textit{Other charges} \quad (1)$$ *Electricity tariff* is equal to the sum price of all the activities involved in the electricity supply chain.	USD/kWh
$$\textit{Distribution Charge} = \frac{\textit{Fixed distribution cost}}{\textit{Net electricity demand}} \quad (2)$$ ***Distribution charge*** is mostly volumetric, i.e., fixed cost is spread on the households' energy use or ***Net electricity demand***. The model calculates the ***distribution charge*** based on the principle that the utility must fully recover the fixed costs, achieving the total revenue requirement.	USD/kWh
$$\textit{Transmission Charge} = \frac{\textit{Fixed transmission cost}}{\textit{Net electricity demand} + \textit{remaining electricity demand}} \quad (3)$$ ***Transmission charge*** is also volumetric; in this case it depends on the households' energy use (***Net electricity demand***) and the energy consumption from non-domestic sectors ***(remaining electricity demand***).	USD/kWh
$$\textit{Household PV adopters} = \int_0^t (\textit{Adoption rate})dt \quad (4)$$ The stock of *Household PV adopters* increases by the *Adoption rate* over time.	Household
$$\textit{Net electricity demand} = \textit{Residential consumption} \bullet \textit{Total households} - \textit{Residential PV microgeneration} \bullet \textit{Household PV adopters} \quad (5)$$ The *Net electricity demand* from the domestic sector, equals the average energy consumption minus the energy provided by the PV systems. *Total households* are the sum of PV adopters and non PV adopters. *Distribution charge* presents greater increases when consumers sell the surplus energy to the electric grid because it produces a higher reduction of residential energy consumption.	KWh
$$\textit{Residential PV microgeneration} = \textit{Size of the PV system} \bullet \textit{Capacity factor} \bullet 720\textit{hours} \quad (6)$$ ***Residential PV generation*** depends on the size of the solar panel and the capacity factor.	kWh/household
$$\textit{Energy bill non PV adopter} = \textit{Residential consumption} \cdot \textit{Electricity tariff} \quad (7)$$ ***Energy bill for non PV adopter*** is equivalent to the average individual households' electricity requirements multiplied by the electricity tariff.	USD/household
$$\textit{Energy bill PV adopter} = (\textit{Residential consumption} - \textit{Residential PV microgeneration}) \cdot \textit{Electricity tariff} \quad (8)$$ The difference between the electricity consumption and residential PV generation is the net demand per household. Depending on his Net demand, a network user could be: (i) a "consumer" if his electricity consumption exceeds the PV generation, taking from the grid the necessary energy to supply his demand; or (ii) a "prosumer" if PV generation exceeds electricity consumption, selling surplus electricity to the grid.	USD/household

units. These equations reproduce the dynamics of the PV adoption represented in Fig. 1, i.e., they reflect the conditions that may lead to a utility death spiral.

3.1. Assumptions

The simulation model is based on the following assumptions:

- PV diffusion is limited to the residential sector.
- Net Metering is assumed as the PV compensation scheme, i.e., PV adopters receive the electricity retail rate for the surplus energy injected into the grid.
- Different scenarios consider that households adopt solar panels of capacity greater than or equal to 1 kW. A 1-kW system is sufficient to offset the average electricity needs of households in the Colombian case.
- Households with PV systems remain grid-connected and solar-plus-battery systems are not considered.
- For simplicity, no difference between distribution utilities is considered.
- Customer consumption pattern is not modified during simulation runs.
- For simplicity, there is not grid investment from distribution companies.
- Average solar radiation was considered, but neither seasonality nor intermittency was considered. Note that Colombia hydroelectricity capacity is very large and complements well rooftop solar.
- The regulatory revenues are set under a revenue cap regulation, which is the approach used in the Colombian electricity market. In addition, it was assumed that the distribution charge is set in advanced and goes into effect immediately.
- The payment of energy bills depends on the affordability of households, i.e., households cannot spend more than their income paying energy bills.
- Levelised cost of electricity for solar PV was calculated using a discount rate of 1.72%; to find this value the average inflation for the last five years was subtracted from a risk-free rate of 4.6%.
- Levelised cost was calculated using an investment cost that varies between 1586 USD/kW and 2551 USD/kW. This cost was determined from enquiries addressed to several PV companies in Colombia. Investment cost is reduced according to a learning rate of 20% (Hayward and Graham, 2013).
- Growth rate is not static; it depends on the Bass model that dynamically compares the PV levelised cost and electricity cost from the grid.

The simulation model uses data provided by several Colombian institutions. For instance, data about electricity demand projections and power projects in construction were taken from The Mining and Energy Planning Unit – UPME (2015); important information for initial conditions, such as the wholesale electricity price and the load curve of the system, were provided by Market experts – XM (2015); the average consumption and electricity tariff breakdown was obtained from the Single Utility Information System – SUI – SUI (2015); and population statistics together with the number of households were obtained from the National Administrative Department of Statistics – DANE (2015).

3.2. Application case

Colombia is used here as a case study. This is a country located in the equatorial zone of South America, with a high sunshine availability and an average solar radiation of 4.5 kWh/m^2/day, which is favourable to photovoltaic deployment (UPME & IDEAM, 2005). Despite its solar potential, the implementation of solar-based resources has been only approximately 9 and 11 MWp (UPME, 2015), respectively, while its generation is greatly hydroelectric (approximately 70%) (UPME, 2015). This article considers the penetration of rooftop solar panels in the residential sector only, although attractive given its great potential − approximately 40% of the total electricity demand (SUI, 2015) – which leaves out the industrial, commercial and institutional sectors – clearly underestimating the overall effect that PV diffusion may perpetrate on the system.

Furthermore, PV diffusion is not only favoured by Law 1715 (Congreso de la República de Colombia, 2014) but also because the technology has reached grid-parity in a great number of urban areas of the country (Jiménez et al., 2014). Although not fully implemented yet, Law 1715 announces some support to renewables, including PV solar. While the effects of the Law are still uncertain, there are nevertheless challenges in the electricity generation and distribution business as discussed in Jimenez et al. (2016) and Castaneda et al. (2017).

In sum, Colombia was chosen for analysis because of the propitious conditions for solar PV development such as high solar radiation, the new Law for renewables and the availability of quality data. Thus, it is necessary to study the transitional actions to help utilities adapt to the changes that could be on the horizon. This research attempts to fulfil this need.

4. Simulation results

This section discusses simulation runs that address the main issues posed at the outset of the paper: In subsection 4.1, the conditions that may lead to the utility death spiral and the options to avert it, seeking to address societal welfare issues are described. The following subsection 4.2 analyses the possible alternatives to avert the utility death spiral using system thinking. Finally, the simulations of some alternatives described in 4.2 are discussed in Section 5.

4.1. What are the market conditions that may lead to the utility death spiral?

Results in this section consider all the assumptions described in Section 3.1, including the fact that only the residential sector can adopt PV systems with a sufficient installed capacity for average electricity consumption, and those PV systems have no battery support for storage. Net Metering is the compensation scheme considered here, and grid capacity is capable of supporting the necessary electricity dispatch. A simulation time horizon of 20 years (2016–2035) was considered to study the mid- to long-term effects of DG development. The reinforcing feedback between PV deployment and the residential tariff or death spiral is displayed in Figs. 3 and 4. As it was explained before, for several Colombian regions, electricity PV cost has already reached grid parity or will imminently reach it in some parts of Colombia. Thus, the increase in the ratio between the electricity tariff and the cost of solar PV leads to increasing PV adoption and self-generation. Net Metering policy enables PV adopters to sell surplus energy to the grid at an electricity retail rate; this along with grid parity could motivate households to install big PV systems to generate more power than the households needs. Death spiral is related to free-rider problem where PV households receive bill savings but maintain their consumption behaviour, making use of a limited resource (the network) to their benefit (back-up and reliability). Indeed, to offset 100% of the average energy consumption for a household, a 1-kW system is enough. The simulation model employed allows testing different PV panel sizes installed per household, 1 kW, 2 kW and 3 kW. The latter case of 3 kW corresponds to a hypothetical case where the free-riding problem is exacerbated and there is no political intervention.

When the size of solar panel is 1 kW, 2 kW and 3 kW, the total PV installed capacity for 2035 is 2.5 GW, 11 GW and 16 GW (see Fig. 3), respectively; supplying 6%, 35% and 62% of electricity generation by 2035. If households are over installed with 3-kW panels, the system will collapse in 2035 (see Fig. 4), and the large-scale diffusion of solar PV will provoke the highest residential tariff because network costs will be

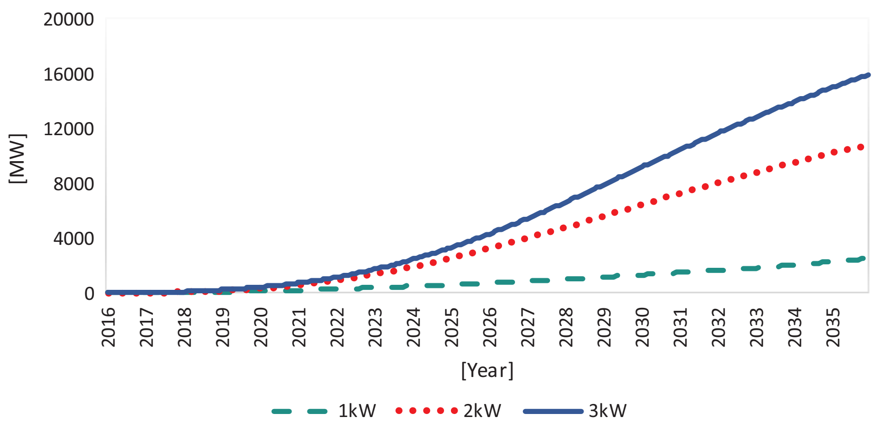

Fig. 3. Cumulative installed capacity of solar PV. Source: Own elaboration.

spread over declining energy consumption from the grid by 2035 – because the total net energy consumption falls prominently in the residential sector for this hypothetical case. By the end of this year, energy consumption of residential sector for a panel size of 2 kW and 3 kW is, respectively, 63% and 101% lower than for panel size of 1 kW. This analysis was also conducted by Castaneda et al. (2017) who obtained similar results to those presented here.

Fig. 5 depicts the energy bill for both PV adopters and non-PV adopters when the average PV panel capacity is 3 kW. The energy bill results from computing the user's net generation or consumption, the retail rate, and the difference between the energy consumed by a customer over a month and the solar energy output of a PV system. Under the Net Metering scheme, the treatment of net excess generation varies from place to place. Commonly, the credits received by the surplus energy supplied to the grid are rolled over indefinitely from one billing period to the next – which is helpful to compensate for a future negative balance (Poullikkas, 2013; Linvill et al., 2013). In addition, the net excess generation may be paid at the retail rate in cash (Poullikkas, 2013; Linvill et al., 2013); that is the case shown in Fig. 5, where in addition, the PV adopter has surplus power during the simulation time. As can be noted, the scenario displayed in Fig. 5 is unsustainable. The earning of the PV adopter is not symmetric with the expenses of the non-PV adopter; this is because over 30% of the population has PV systems, so fixed costs are mostly spread over 70% of the population. Although unrealistic that the system will provide such big profits, this shows the potential benefits of free-riders to deceive the system or it will motivate many others, including industry and commerce, to move into PV generation.

Network reliability is a public good and a shared resource; the cost of serving one network user depends on the services provided to other users (Sakhrani and Parsons, 2010); as solar PV adopters only consider the value to themselves, not to the system as a whole, this leads to free-riding (see Fig. 5). A PV adopter could make money from current market conditions associated with a death spiral–but if everyone becomes a prosumer, the network reliability is destroyed, and everyone loses because all residential customers are still connected to the grid. Here, the necessary conditions for a death spiral are identified, likewise, its effects on distribution utilities and customers; possible dynamic solutions for this phenomenon are identified in the next section.

Although a scenario with over size PV systems of 3 kW seems unlikely, this scenario is equivalent to a scenario where other customers in addition to households become prosumers (commercial and industrial customers) and Net Metering scheme leads to an opportunistic behaviour ("free-rider") by the customers (see, e.g., Castaneda et al., 2017). In addition, Fig. 6 suggests a scenario of economic progress for households where they remain with oversized PV systems (1.7 kW per household), after a longer timeframe (2016–2060); this intermediate scenario shows the unfeasibility for utilities through a growing residential tariff.

4.2. Can the regulator and utilities avert a death spiral achieving social welfare?

The previous section shows that the utility death spiral is conceivable if every household adopts a PV system much larger than needed or under a longer timeframe. The challenge for the policymaker is thus to integrate the PV systems ensuring system sustainability, i.e., affordability to customers. This subsection discuses alternative systemic market interventions that can be implemented to address death spiral problem, including (i) reducing the ratio between the electricity tariff and the cost of solar PV, by internalising the transmission/distribution costs involved in back-up-support to household, which in turn will increase the transition costs of solar PV systems; (ii) modifying the methods of compensating prosumers (e.g., Net Metering)

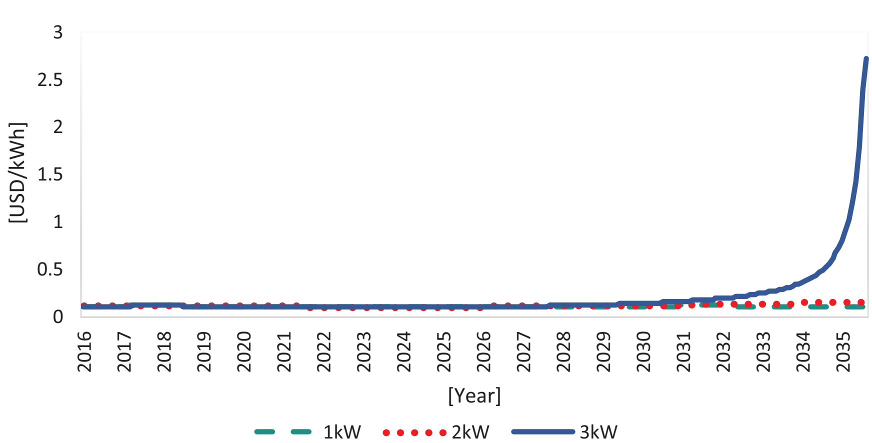

Fig. 4. Residential tariff for different panel sizes. Source: Own elaboration.

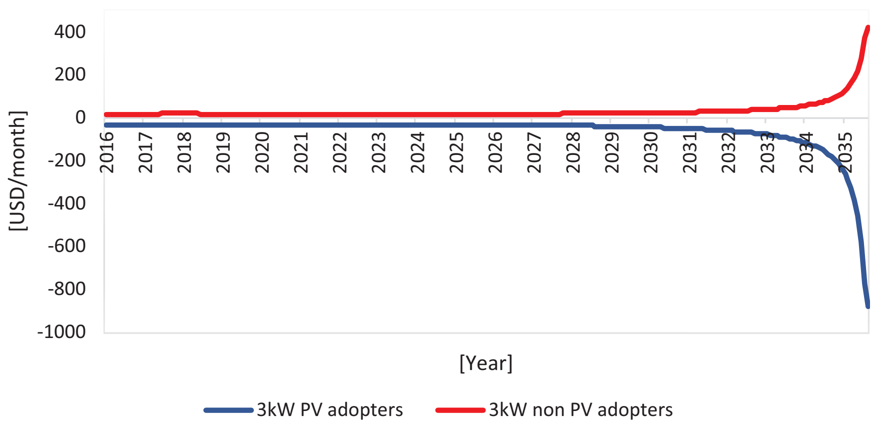

Fig. 5. Energy bill for customers for a panel size of 3 kW. Source: Own elaboration.

to reduce the incentives to install oversized PV arrays; (iii) changing the polarity of the reinforcing loops R2 and R3 in Fig. 1, through tariff changes. Additionally, utilities can take different stands in order to protect their business models from the death spiral, taking such actions as (iv) proactively changing their business model; and (v) strategically costing their services (Costello and Hemphill, 2014; Poisson-de Haro & Bitektine, 2015).

4.2.1. Implementing a back-up fee

Some power markets may opt to add a back-up fee or differential cost to DG customers, arguing a cross subsidy in favour of DG customers (Eid et al., 2014). Cross subsidisation means that DG customers would benefit from grid service at no cost, but these costs would be transferred to non-DG customers because utilities must increase rates to meet their revenue requirement (Picciariello et al., 2015a). The back-up fee has been applied in several markets, such as in Spain, where DG customers have to pay fees on solar self-consumption (Ministerio de Industria Energía y Turismo de España, 2015; Lopez and Steininger, 2015). Back-up fee covers the usage of the network by PV owners, i.e., network access tolls and adjustment services. In Spain, it has two components: a fixed part, based on the capacity installed (power contracted with the electricity company plus PV capacity installed), and a variable part for the electricity self-consumed from the PV installation itself (Lopez and Steininger, 2015).

Fig. 7 is the same as Fig. 1 but the latter shows how as a back-up fee is added to the electricity cost of Solar PV cost, this reduces the adoption of PV, controlling the utility death spiral because the balance feedback loop B1 compensate the reinforcing effects of feedback loops R1, R2 and R3.

Eq. (9) shows the mathematical formulation of the levelised cost, where a back-up fee is added to the costs associated with the PV investment in time t; these costs are discounted and divided by the net present value of the electricity generated for the solar PV system during

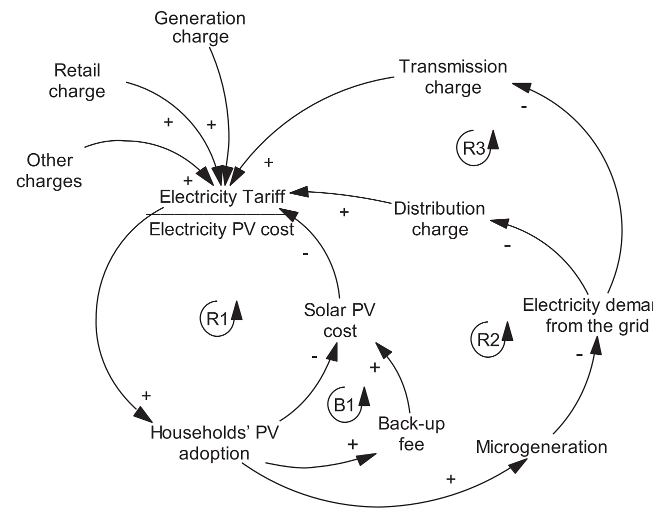

Fig. 7. Back-up fee measure for averting death spiral. Source: Own elaboration.

its lifetime, where n is the lifetime of the system and r is the discount rate:

$$LCOE = \frac{\sum_{t=0}^{n} (Costs(t)+Backupfee(t))/(1+r)^t}{\sum_{t=0}^{n} Energy(t)/(1+r)^t} \tag{9}$$

Some may argue that this regulation increases PV costs–due to the internalization of the back-up fee cost, see Eq. (9) –dampening the PV development and therefore hindering the decarbonisation of the power sector. In addition, this measure may be difficult to implement in countries with high penetration ratios. However, it is important to consider this alternative for a sustainable transition of DG.

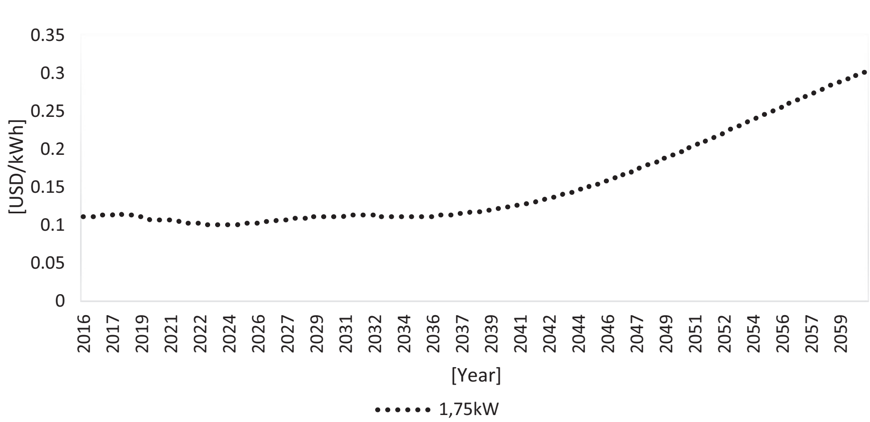

Fig. 6. Residential tariff for 1.7-kW PV panel size and a longer timeframe. Source: Own elaboration.

4.2.2. Shifting from net metering to net billing

Net Metering is a mechanism that compensates distributed solar generators at the retail rate for the energy supply to the grid (Darghouth et al., 2014). Net Metering rules have become controversial during recent years due to the possible impacts on the public and utilities (Eid et al., 2014; Hess, 2016). The arguments to modify Net Metering rules are based on the following: (i) it could create a cross subsidy in favour of DG customers, which leads to the same justification of the back-up fee (Hess, 2016); and (ii) PV generation and electricity are traded by volume, and wholesale energy price may be considered to compensate PV generators.

Therefore, the proposal for alternatives to Net Metering includes limiting DG solar (limit the amount of power generated or the size of installations) or making compensations in terms of electricity price at the time when is being supplied (Hess, 2016; Rule, 2015). Section 4.1 demonstrates that restricting the size of individual PV systems averts a death spiral. However, there is a more suitable option than reduce the incentives to oversized PV system, which is Net Metering with rolling credit where PV adopters receive credits for selling excess energy into the grid instead of money; credits should be used before a time of expiration to lower electricity bills.

Net Billing is an alternative to compensate net excess generation, where the energy exported to the grid is sold at avoided costs (usually wholesale price plus avoided losses), while the energy imported from the grid is bought at the retail rate (Watts et al., 2015; Dufo-López and Bernal-Agustín, 2015).

In Colombia, residential peak demand and PV system output do not match (Jimenez et al., 2016) Fig. 8 displays how a Net Billing scheme to the residential sector of Colombia would be, although Net Billing is not currently applied in that country, additionally, Fig. 8 would change according to the particular daily sun availability, any possible PV dispatchability restrictions during some days (and seasons), as well as according to the use of batteries. As can be observed in Fig. 8, the surplus is paid at a lower cost than the retail rate, which reduces the benefit from exporting net excess generation; these effects are displayed in Fig. 9 (cycle B1).

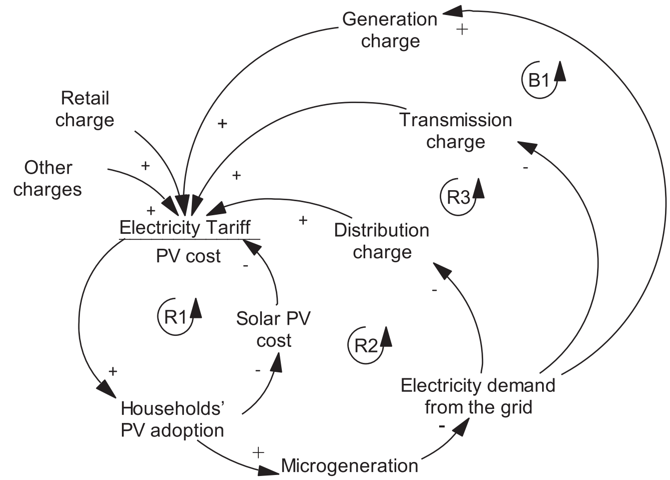

Fig. 9. Net Billing measure for averting a death spiral. Source: Own elaboration.

Under Net Billing the energy bill for a PV adopter would change; the net excess generation would be paid at a lower rate than under Net Metering (See **Eq.** 10 and **8,** respectively).

$$EnergybillPVadopter = (Residentialconsumption) \bullet Electricitytariff - ResidentialPVmicrogeneration \bullet Surplusprice \quad (10)$$

4.2.3. Changing tariff design

In most countries, network costs are recovered from a volumetric charge that is levied on each unit of energy consumed (Eurelectric, 2013). Some may argue that under current tariff design (based on volumetric charges), the rise of DG could promote cross-subsidisation and network unsustainability, thus the need to modify tariff designs seeking sustainability, economic efficiency and consumer protection (Sakhrani and Parsons, 2010; Rodríguez Ortega et al., 2008; Pérez-Arriaga et al.,

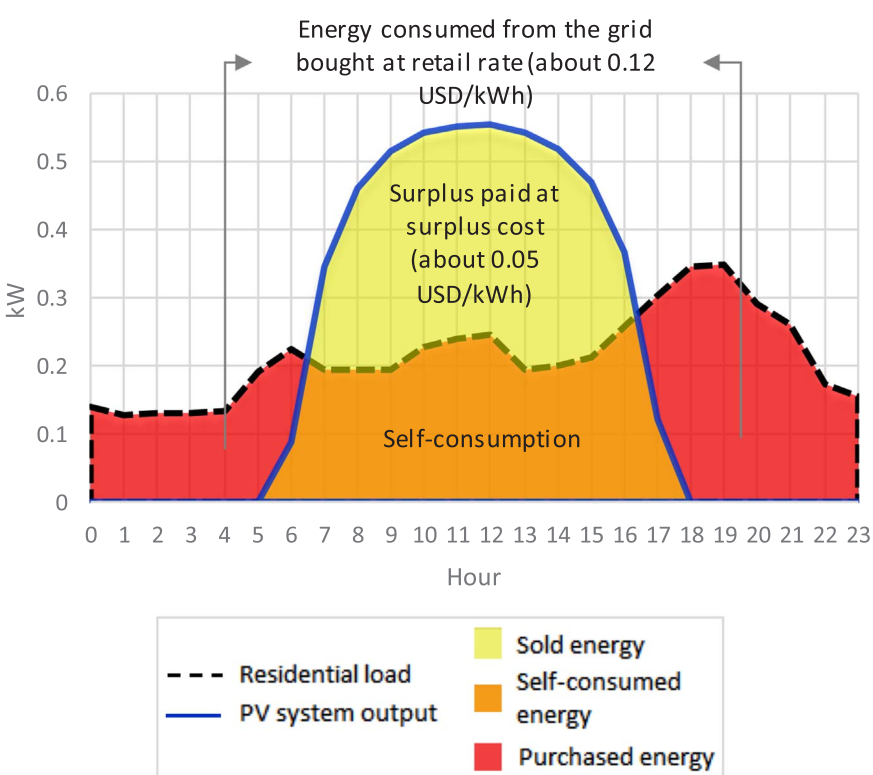

Fig. 8. Net Billing applied to the residential sector in Colombia. Source: Own elaboration.

2013; Picciariello et al., 2015b). Cross-subsidies contradict the following principles for rate design: cost-causality (customers are charged according to efficient network management) and equity (customers are charged the same for the same use of the network) (Eurelectric, 2013; Pérez-Arriaga et al., 2013). In power systems where there is not a match between load profile and PV system output, DG customers may consume energy from the grid at peak times. DG customers pay energy bills based on energy consumption (kWh) without contributing to the peak demand, which is the main driver of network costs.

Thus, volumetric charge is unsuitable to reflect the true costs of providing networks' services, as the costs incurred by a utility depend not only on power flows. As network costs are mainly fixed, some researchers propose an alternative rate design that increases the fixed portion of the bill paid by the customers (Brown and Lund, 2013). The fixed charge payment is similar to the back-up fee but the former also includes connection charges and some administrative costs. Opponents argue that increasing fixed charges reduces the incentives for efficiency and solar investments (Lacy et al., 2012). Indeed, this measure may reduce the revenue erosion of utilities but also promote the adoption of batteries, exacerbating financial problems for utilities (Satchwell et al., 2015b). Others argue that networks are appropriate for meeting a peak demand, and therefore, rates should include a demand charge applied on the consumers' maximum demand (kW) during a specific time range (Firestone et al., 2006), which may incentivise demand response and energy storage. Another tariff design option for network tariffs is a time-varying rate such as time-of-use (TOU) pricing, where different prices are associated with periods of time, reflecting the real-time value of wholesale energy (Bergaentzlé et al., 2014). A time-varying rate may incentivise energy efficiency, demand response and energy storage; the latter could be used to supply balancing services to the grid (Brown and Lund, 2013).

In Fig. 10**,** the reduction in the electricity demand due to PV generation is compensated by the increase in the fixed portion of the distribution charge, which leads to a lower distribution charge. The balance feedback loop B2 compensates for the reinforcing effects of feedback loops R1, R2 and R3.

For a network tariff that comprises a volumetric charge plus a fixed charge, the energy bill for a PV adopter would be as shown in Eq. 11:

$$
\begin{aligned}
&\mathit{EnergybillPVadopter}\\
&\quad = (\mathit{Residentialconsumption} - \mathit{ResidentialPVmicrogeneration})\\
&\quad\ \bullet(\mathit{Generationcharge} + \mathit{Distributionchargevolumetricportion}\\
&\quad\ + \mathit{Transmissioncharge} + \mathit{Retailcharge} + \mathit{Othercharges})\\
&\quad\ + \mathit{Distributionchargefixedportion}
\end{aligned}
\tag{11}
$$

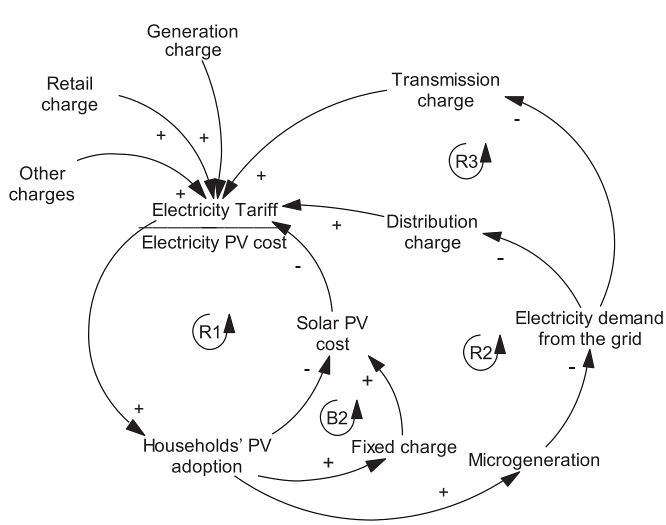

Fig. 10. Fixed charge for averting death spiral. Source: Own elaboration.

4.2.4. Rethinking business models

Reinforcing feedbacks R2 and R3 in Fig. 1 depict behaviour when first, utilities expectations are myopic, i.e., utilities focus on maximize short-term profits to the detriment of mid- to long-term returns, increasing rates when PV adoption increases; and second, there is inaction by the regulator, which may intervene by setting a cap on network charge.

Utilities could adopt different strategies to face the challenges imposed by renewable energies, e.g., a proactive strategy to reinvent old business models and retaining the position in the market could be an alternative. The development of distributed energy resources has increased the need for innovative approaches to integrate these resources in the planning and operation of the grid; an integrate grid entails a power system transformation where new business models might evolve. In addition, network operators might gain opportunities from these new business models, including more services to realize full value of distributed energy resources, which are a potential flexible tool for power trade and system balancing (Pérez-Arriaga et al., 2013). However, it is necessary to clarify that new business models are beyond the scope of this article and therefore are not considered here.

5. Simulating systemic interventions to avert a death spiral

SD modelling enables simulations of different systemic interventions to smooth transition to other business models. This section uses as reference the most extreme scenario of the utility death spiral, where each PV household installs a 3-kW solar system, seeking a robust solution.

As discussed earlier, different alternatives could help the transition towards the full development of DG. This section assesses through simulation how the specification of a back-up fee, Net Billing and fixed charge may help. The section investigates how the different nature of these options may provide alternative solution to the death spiral issue. On the one hand, a back-up fee internalizes the cost for PV adopters diminishing the willingness to adopt. On the other hand, Net Billing reduces the earnings received by PV adopters in comparison to Net Metering, as the energy injected into the grid is compensated at a lower price than the retail rate. Finally, the fixed charge approach does it by reallocating the grid charges in proportions 70/30 or 80/20 to a mix of fixed charge plus volumetric charge, respectively. These values have been obtained as the minimum portion of fixed charges that avert the utility death spiral in the most catastrophic scenario of 3-kW solar systems.

Below, a back-up fee is analysed through a sensitivity analysis of PV cost. The modelling results show that after implementing a back-up fee, from 2016 onwards the PV electricity cost could increase by 25% (an additional 38 USD/kW per year) and 50% (an additional 83 USD/per year) with respect to the reference scenario; resulting in 20% and 36% less of installed PV capacity by 2035 regarding to the reference scenario, respectively (See Fig. 11). Fig. 12 presents the residential tariff associated with each level of PV penetration, which is shown in Fig. 11, and as can be observed, the system collapse provoked by a death spiral is averted when electricity PV cost is high, at least during the simulation period.

Fig. 13 depicts the residential tariff under Net Billing and a fixed cost policy. Both policies attain both a low residential tariff–the catastrophic death spiral is deterred. With Net Billing, the installed PV capacity is lower at 43% regarding the reference scenario in 2035. For the same year, distribution charges with a 70% and 80% fixed portion produce a decrease in PV power capacity of 32% and 39% compared to the reference scenario, respectively.

This analysis has helped to identify the systemic interventions to avoid death spiral effects – ensuring low tariffs for customers and cost recovery for utilities. Particularly, a back-up fee, Net Billing and a volumetric/fixed charge are measured that slow down PV adoption during the simulation period. Table 2 shows that the scenario with a

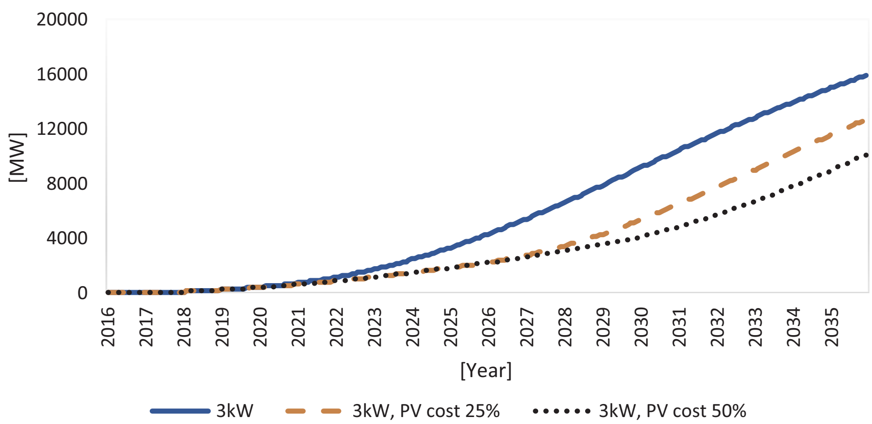

Fig. 11. Sensitivity analysis of PV installed capacity under different levels of electricity PV cost. Source: Own elaboration.

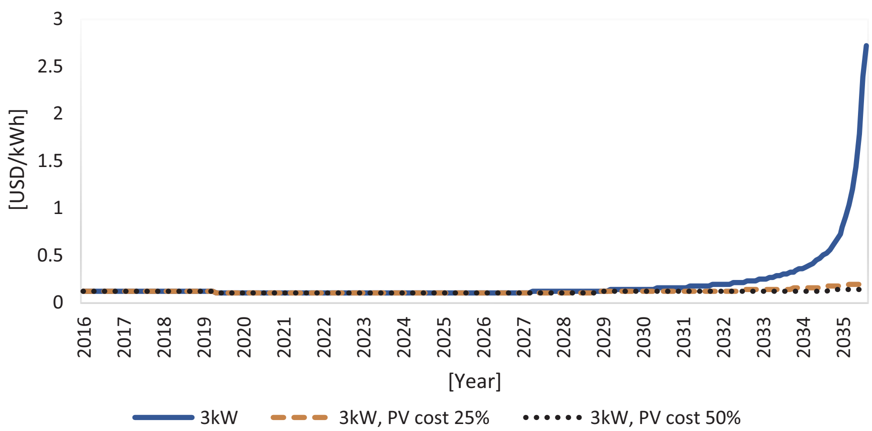

Fig. 12. Sensitivity analysis of residential tariff under different levels of electricity PV cost. Source: Own elaboration.

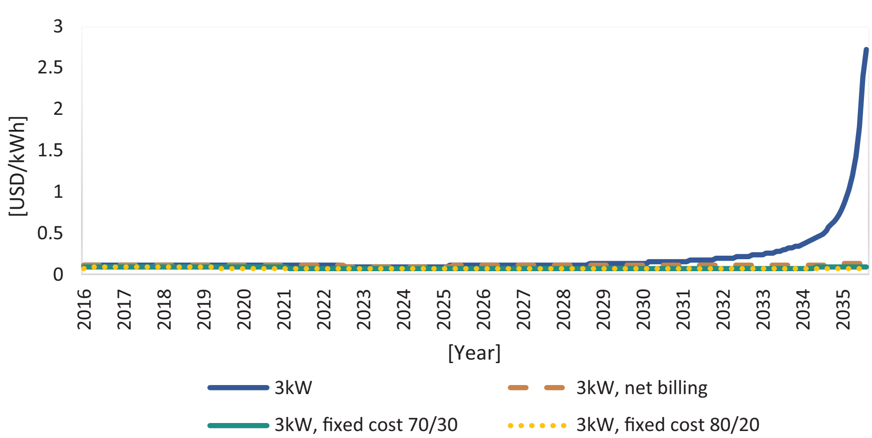

Fig. 13. Residential tariff under different tariff designs. Source: Own elaboration.

Table 2
Effects of policy interventions on PV deployment, customers and utilities.
Source: Own elaboration.

Scenario	PV cumulative capacity (MW)	Electricity supplied from solar PV	Annual percentage growth rate of PV adopter's revenue	Annual percentage growth rate of non PV adopter's expenses	Cost recovery for utilities by 2035
3 kW reference scenario	15,918	62%	18.4%	18.4%	0%
3 kW PV cost 25%	12,693	44%	3.3%	3.3%	85%
3 kW PV cost 50%	10,134	32%	1.3%	1.3%	100%
3 kW Net Billing	9142	28%	1.4%	1.1%	100%
3 kW fixed cost 70/30	10,783	35%	1.4%	1.1%	100%
3 kW fixed cost 80/20	9661	30%	1.4%	1.1%	100%

volumetric plus fixed charge (70/30) offers the greater level of PV investment along with affordability for customers and full cost recovery. Additional simulation runs, which are not reported in this paper due to space constraints, have shown that the system may collapse again under a longer timeframe for all the measures analysed here. This demonstrates that the power transformation is unavoidable and that during the transition period, the regulator should find innovative ways to integrate distributed energy resources into the grid, ensuring environmental quality, affordability and reliability.

The following section discusses deeply valuable lessons derived from this research, useful lessons to support regulators and utilities to face the power sector transformation towards a more decentralized system where distributed generation plays a leading role.

6. Conclusions and policy implications

This paper explores the conditions, effects and several interventions for a smoother technology transition in electricity. The objective of this paper has been achieved, as it has identified important determinants of the utility death spiral and alternative policy for the technology transition from a systemic and sustainable perspective.

Regarding the death spiral determinants, the results indicate that a utility death spiral is possible when some vicious cycles occur, where the electricity PV cost, the electricity tariff and the PV adoption rate for customers are critical variables. The developed simulation model indicates that for an average PV-panel size per household of approximately 2 kW or higher, the utility death spiral occurs, and the system collapses, as the electricity tariff will be too expensive to be paid for customers, and the utilities could not recover their costs. Furthermore, this situation infers that if industrial, commercial and institutional customers adopt PV panels, the utility death spiral is more likely to occur sooner rather than later. This result could be worse if customers become autarkic by using PV systems and batteries, although some studies indicate that grid defection is not yet an economically feasible option (Khalilpour and Vassallo, 2015; Bronski et al., 2014).

Mid- to long-term consequences of the death spiral of the incumbent electricity distribution business include sales decreases as the result of greater PV adoption and greater revenue losses for utilities; in addition, grid users with solar PV systems will experience benefits while the non-PV adopters will face very high tariffs. The mentioned effects not only harm the utilities traditional business model, but may also put at risk the entire system sustainability and the societal welfare. Specifically, public goods affected by a death spiral include grid reliability: if large numbers of customers become prosumers, the network reliability is destroyed, and everyone loses because households remain connected to the grid and electricity distribution becomes unsustainable. This situation suggests that efforts to protect the system from a death spiral's negative effects would assist in a smooth technology transition of the power supply system.

Regarding these concerns, different strategies for a smoother and sustainable technology transition in energy were analysed using a simulation model. This set of strategies includes the implementation of back-up fee, Net Billing and increasing fixed charges. These are short- to mid-term solutions for the technology transition to PV distributed generation, aimed at achieving social welfare as affordability and development of solar PV systems are initially ensured. However, the longer time framework requires further institutional developments as the broad penetration of solar DG seems unavoidable with further boosts in battery support, but this goes beyond the objective of the paper. Therefore, Colombia may seek opportunities from this technological change.

Finally, for the Colombian case, it is possible in the short-term, to avert the death spiral issue through systemic intervention, safeguarding not only the utilities' profitability but also the system reliability and social welfare. Although the case discussed in the paper is country-specific, certain of the findings may have similar implications in other parts of the world.

The paper succeeds in its purpose on at least two counts: a) it shows the likely effects of solar PV in the residential sector; b) it establishes the conditions under which a distribution charge fails, and c) shows by simulations the long-term effects of different strategies to mitigate the death spiral effect. Future research may include simulation of alternative tariff designs and compensation schemes for customers, as well as battery storage support and changes in consumption patterns.

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