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# Evaluating the effect of technology transformation on the electricity utility industry

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ABSTRACT

The technology shift from fossil-fuelled systems to renewable energies has been promoted by governments with the purpose of decarbonising the power industry. However, rapid technology progress has prompted disruptive changes that transformed market structures. Incumbent electricity utilities, particularly those based on fossil-fuel plant, are shifting from their stable and predictable situation to confront challenges from those that offer alternative energy services. In this new environment, the industry will benefit from mid- to long-term sector foresight.

The paper studies the potential impact of renewable energy sources (RES) on electricity systems, specifically on the generation and distribution businesses. For this purpose, a fairly detailed and integrated supply and demand-based system dynamics model has been built to quantify the extent of their potential impact; the model disaggregates the household sector, which may generate a significant part of its electricity using rooftop solar energy. This is illustrated by examining a utility engaged in the generation and distribution businesses in the Colombian electricity market. Through simulation runs, this paper concludes that, subject to policy and all other things remaining equal, solar rooftop generation is a major threat for utilities; while the generation business is most affected in the short-term, the distribution business is the one most impacted in the long-term, and jointly they may induce the utility "death spiral".

## 1. Introduction

In the late 1980s, following market efficiency principles, the liberalisation of the electricity industry was pioneered by Chile (1982) and Britain (1990), and soon after they were followed by many other countries around the world [1,2]. Nonetheless, as governments have presently set targets for decarbonisation and renewable generation, it seems that there is a shift towards a more centralised view of markets, as current liberalisation does not provide signals to meet investment goals with low-carbon generation [3,4]. Under these conditions, as renewable energy is becoming a political priority of governments around the world, electricity utilities face both a rapid technological transformation and regulatory uncertainty [5].

According to Schleicher-Tappeser [6], the technologies with significant potential for disrupting the electricity sector are solar and wind energy, the former to a greater extent than the latter; here, a 'disruptive' technology usually means "cheaper, simpler, smaller, and frequently, more convenient to use" [7]. Some authors have compared the disruption by renewables in electricity with that which took place in the telephone industry, in electric lighting, and in digital photography [8]. Regardless of the similarities with those cases, renewable energies are certainly transforming electricity markets [9]. Though the upcoming transformation offers great opportunities, it also poses regulatory and institutional challenges to the power industry as regards quality and reliability, such as the intermittency created by the deployment of solar photovoltaic technology (PV), as is now the case in Germany where distributed PV stands at 36 GW, over a peak load range of 40–80 GW [10].

Further, as electricity generation is shifting from fossil- to renewable-based technologies, utilities will need to confront the impact of environmental and energy policy changes on their current business model. In this direction, as the industry is experiencing a rapid penetration of renewables and as a good number of their customers will eventually self-generate a significant portion of their own needs from rooftop PVs, it is not completely clear how incumbent utilities may create value, and many are therefore venturing into new business models [11].

For studying the effect of technology transformation on the

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electricity utility industry, country specifics are important. Developing countries with a high share of hydropower confront challenges with the penetration of renewables energies, such as: i) power shortages and electricity price increases during dry seasons; ii) high intermittency and seasonality in power supply; and iii) financial impacts on utility businesses [12]. Thus, this paper considers the Colombian electricity market, which is characterised by a high share of hydropower resources combined with some thermo-power dependence.

Though much has been written about the likely impacts of renewable energies on electricity markets [13–16], the literature that focuses on the long-term effects of renewable energies on electricity utilities is not abundant, and there is even less of it from a systems-modelling perspective, with little of that focussing on the developing world. The paper studies the potential impact of renewable energy sources (RES) on electricity systems, specifically on the generation and distribution businesses, in the case of Colombia.

The paper is structured as follows. Section 2 discusses the impacts of renewable energy on utilities. Section 3 presents the simulation model that has been built to assess the impact of renewables on utilities, the main equations involved, the dynamic hypothesis of this research, model assumptions, data sources and scenario description. Section 4 incorporates research outcomes, and Section 5 provides the conclusions of this paper.

## 2. Impacts of renewable energy on utilities

Renewable technologies such as onshore wind and solar PV are penetrating swiftly in several geographic areas, worldwide [17]. While China (145.4 GW), the United States (74 GW) and Germany (45 GW) are the top three countries with wind power capacity in place, the top three for solar installed capacity are China (43.5 GW), Germany (39.7 GW) and Japan (34.4 GW) [17]. This section discusses how the penetration of renewables may impact the electricity generation business and the integrated utility business (where the generation and distribution businesses are combined), and discusses the modelling approaches that have been used to assess the extent of these impacts.

### 2.1. Impacts on the electricity generation business

Though renewable energies have great potential and many positive impacts in the electricity sector and society as whole, there are concerns about the challenges to the incumbent electricity utilities having assets in conventional energy sources [18]. A possible challenge for utilities is the "merit-order effect" that occurs when most renewable energies have low or negligible variable costs, thus displacing conventional generation (See Fig. 1), and inducing a low wholesale electricity

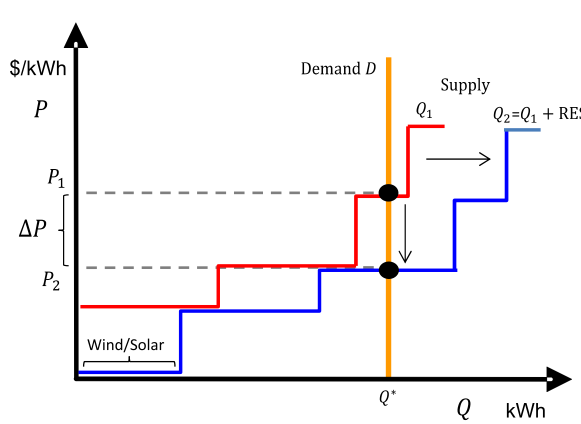


**Fig. 1.** Decrease of power price due to additional Renewable Energy Sources (RES) in the supply curve (merit-order effect).
Source: Authors.

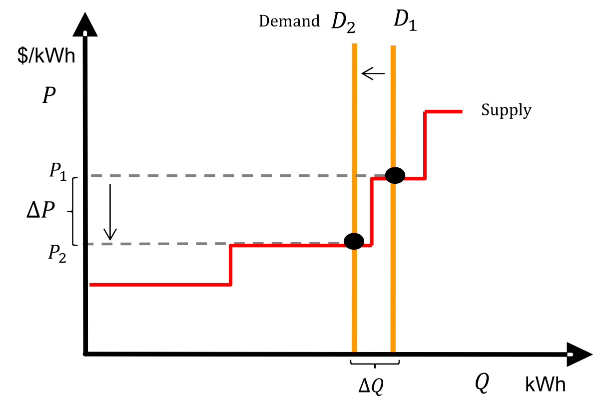


**Fig. 2.** Power price formation by reduction of electricity demand due to Distributed Generation (DG).
Source: Authors.

price [19,20]. This may result in lower profits to the incumbent electricity generation business with stranded assets.

In a similar direction, as distributed generation (DG) encourages customers to produce their own energy, the incumbent generators may face a reduction in their energy sales [21] and a reduction in the marginal electricity price (See Fig. 2).

In the presence of renewables, it is important to take into account the merit-order effect as it would prompt changes in the incumbent utility business model since electricity demand could be predominantly satisfied by renewable energies. Thus, only a highly flexible generation fleet would be needed – for balancing purposes [15,16,18,19].

The reduction of wholesale electricity prices in Germany is clear evidence of the merit-order effect, which has also been experienced in other countries, such as Spain and Italy [22,23]. The swift decline in wholesale electricity prices in Germany has reduced the profitability of electricity utilities such as E.ON and RWE (formerly *Rheinisch-Westfälisches Elektrizitätswerk AG*), which has led E.ON to adopt a radical new strategy by divesting its conventional plant – shedding 13 GW of thermal generation assets – and instead focusing on renewables, DG and customer-support solutions [24].

### 2.2. Impacts on integrated utility business

The greatest threat from DG development is its reinforcement of the integrated-utility "death spiral" (Fig. 3) that results from the utilities' need to increase tariffs to compensate for the reduction in electricity demand from them. Consumers with PV panels produce their own energy, therefore buying less energy from the grid, further promoting solar PV adoption, which leads in turn to further tariff increases [25–

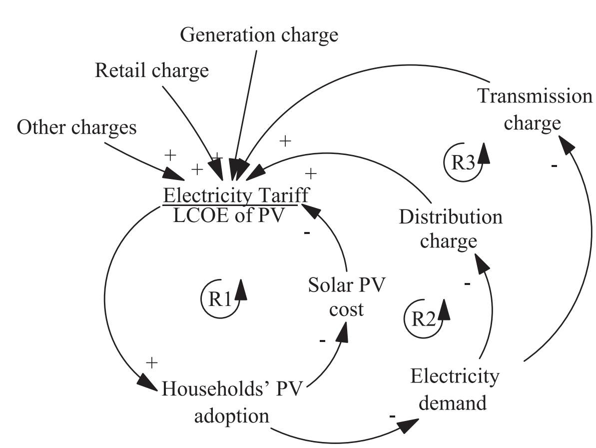


**Fig. 3.** Utility death spiral.
Source: Authors.

28]. The dynamic hypothesis in Fig. 3 shows, with the help of arrows, causal relationships between pairs of variables; an arrow from variable $x$ to variable $y$ could have a positive or negative sign on it, which implies a positive/negative relationship – i.e. an increase/decrease in the variable $y$ is caused when variable $x$ increases.

For simplicity of argument, this research shows how the penetration of rooftop PV panels in the residential segment alone may be sufficient to illustrate the disturbing effect of DG on the country's electricity utility industry. Fig. 3 displays the utility death-spiral hypothesis: Households compare the electricity tariff with the levelised cost of electricity (LCOE) from PV in order to decide on their choice of electricity supply. The LCOE of PV (Eq. (1)) is defined as the cost per unit of generated electricity; it 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 ($n$ years) [29]. As the ratio of the electricity tariff to the LCOE from PV increases, more households adopt PV panels. Loop R1 shows how technology learning-effects induced by the greater adoption of solar PV prompt PV cost reduction, causing a higher ratio of tariff to cost of solar-PV. Thus, increases in the aforementioned ratio lead to more customers deploying solar PV, reinforcing loop R1. As in most countries, network charges are volumetric, i.e., depend on energy usage; when PV adoption increases, electricity demand from the grid decreases, forcing utilities to raise network charges to compensate for the energy usage reduction and thereby cover the network costs (see reinforcing loops R2 and R3). These reinforcing cycles refer to the death spiral that leads to a growing number of PV-adopters. Although the utility death spiral has been discussed by other authors, one of the main contributions of this paper is to demonstrate this from a systems-modelling perspective.

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

where $t = year\,(0,\ 1,\ \ldots n)$

The diffusion of renewable DG could enable a cleaner and more efficient power system; however this technology transformation involves changes for the incumbent utilities, which has motivated significant research on death-spiral-related issues [25,27,30], particularly on model-based research to assess the mid- to long-term quantitative effects of the diffusion of PVs [21,31–33]. In consideration of such concerns, this paper investigates the extent of the impact of the penetration of renewables on the electricity system, particularly on the integrated utility industry.

### 2.3. Modelling for assessing the extent of impacts

A broad spectrum of literature – based on the use of classical market models [34,35] – reports on the extent of the impact of large-scale penetration of renewables on power markets, particularly on integrated utilities. For instance, Ballester and Furió [36] statistically test the effect of RES on wholesale markets; Brouwer et al. [37], using an optimisation model, quantify the impact of large-scale intermittent renewable energy on the power system and on thermal generators; and, Sensfuß et al. [20] use an agent-based approach for the German case.

A number of researchers have investigated the financial effect of the penetration of PV-based DG on different stakeholders of the markets [30,33,38,39] – these studies have not taken into account the long-term dynamics of the system. Although many others have incorporated feedback cycles [21,32,40–42] none of them have considered the integrated utility from a systems-modelling perspective, and in particular have ignored the dynamic effects between the wholesale power market and the technology diffusion of solar DG. A few authors, such as Grace [31], Laws et al. [43] and others [41,42,44,45], have used System Dynamics (SD) to assess the effects of PV DG on rates, but they have disregarded the dynamic effects of them on the wholesale power market.

Of all available modelling alternatives, this paper has considered a systems modelling perspective as it facilitates high levels of aggregation, the understanding of dynamic feedback processes and other complexities. Accordingly, for better understanding the potential impact of renewable energies on the electricity system, this approach was chosen over others because of its capability of modelling the highly dynamic power markets, characterised by investment cycles that involve lags, nonlinearities, and feedbacks [46–48]. These features are not always incorporated in classical market models that have no interest in transitional stages but rather focus on equilibrium phases [49].

In summary, there is extensive research about the effects of RES on power markets and utilities. However, none of it takes a systems perspective on a highly hydroelectricity-based country in the developing world. This paper thus aims at studying 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. In this way, the paper further studies the consequences of the technology transformation using economic and social as well as environmental indicators.

The next section provides a broad description of the basic dynamic hypothesis of the market, the main components of the model that has been built, some of the most important equations and information used, and the simulation scenarios that have been considered.

## 3. Modelling the impact of renewables on the Colombian electricity market

In order to assess the extent of the impact of RES on electricity markets, this section describes and justifies the case study, the utility that has been selected, the model that has been built, and the scenarios under which simulations will be run.

### 3.1. The country case study

The research problem posed has been examined for the Colombian case. As discussed earlier, Colombia offers an excellent opportunity to analyse the impacts of renewables on the power industry, including utility businesses. The Colombian electricity market adopted in 1994 the pool-based British design: unbundling the generation, transmission, distribution and trading businesses, and creating competition in generation and trading, according to the liberalisation trend that dominated the industry at the time [50]. Regarding technology, Colombia has a high share of hydropower (about 70% of the total installed capacity) and a high potential for non-conventional sources of energy. The average solar radiation is 4.5 kWh/m$^2$/day and the wind power potential in the northern region is 21 GW (exceeding its current installed capacity, which amounts to 16 GW) [51–53]. Additionally, the government has taken an important step to support the development of renewable energies, through Law 1715 [54].

This involves risk, considering that: i) sustained growth in electricity demand could lead to power shortages due to droughts caused by El Niño phenomena [50]; ii) disregarding grid imperfection, during an average rainy season hydroelectricity is capable of meeting 100% of demand; iii) as electricity dispatch operates according to merit-order rules, there are no market incentives to *firm* energy – the capability of delivering energy during dry periods – different from the capacity mechanism in place; and iv) as Colombia faces natural gas shortages, some thermal generation operates with imported liquid fuels at a price as high as 25 USD/MWh, which, given the logistical expenses, makes it unsustainable as the system price peak is not much higher than 15 USD/MWh. In the short- to medium-term, imported gas is not a solution as infrastructure is inadequate.

In summary, the Colombian electricity market was chosen as a case study because: a) it has great potential in non-conventional energy sources such as wind and solar PV, b) utilities could be affected by

**Table 1**
Installed capacity of Company A and Colombia.
Source: Own elaboration based on [53].

| | Installed capacity of Company A [MW] | Total installed capacity in Colombia[MW] | Share of Company A in total installed capacity [%] |
|---|---|---|---|
| Gas | 770 | 3490 | 22% |
| Coal | 0 | 1016 | 0% |
| Hydro | 947 | 10,390 | 9% |
| Run of river | 113 | 585 | 19% |
| Wind | 0 | 18 | 0% |
| Biomass | 51 | 77 | 66% |
| Geothermal | 0 | 0 | 0% |
| Total | 1881 | 15,577 | 12% |

government action as there are commitments to a 20% reduction of greenhouse gas emissions by 2030, and c) the new Law 1715 favours non-conventional renewable energies [54,55].

### 3.2. The utility case

In Colombia, the power generation market is moderately concentrated: in 2015, the Herfindahl–Hirschman Index (HHI) was 1,507, where the six largest power companies represent about 87% of the total installed capacity in the country, and few of them participate in both the generation and distribution business. In relation to the distribution business, 70% of the companies account for less than 10% of the network assets, therefore most distribution companies are small. This research disaggregates the power/distribution assets of a representative Colombian company (termed “Company A”) from the rest of the utilities, to analyse the effect of renewables on this utility. Company A holds 4% of Colombia's distribution assets and 12% of its power capacity; this capacity totals 1881 MWs, as indicated in Table 1. Note that for the purpose of comparison/validation, the whole utility industry was also studied, in the same manner, and findings were similar to those reported here for Company A.

### 3.3. Modelling perspective

Following the standard SD approach, the dynamic hypothesis proposed in this paper enables the exploration of threats to the Company A by considering different aspects of the penetration of renewables into the electricity system.

Fig. 4 shows the electricity market dynamics, where the capacity margin depends on the difference between electricity demand and installed capacity; when the capacity margin (also known as reserve margin) is tight, electricity price increases, which has an effect on electricity demand (see feedback loop B1). Electricity price provides a signal for capacity investment; this produces overcapacity after a construction time or delay, and this surplus capacity then leads to a lower wholesale electricity price (see feedback loops B2 and B3).

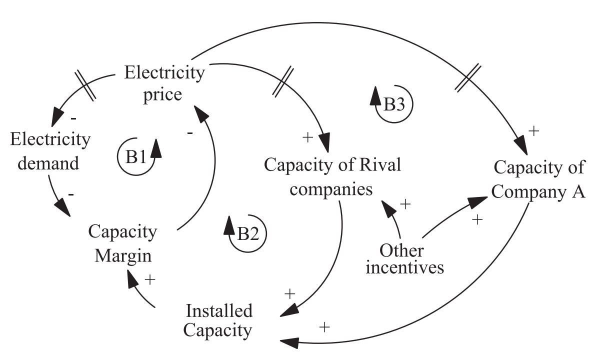


**Fig. 4.** Dynamic hypothesis of the electricity market.
Source: Own elaboration based on [47].

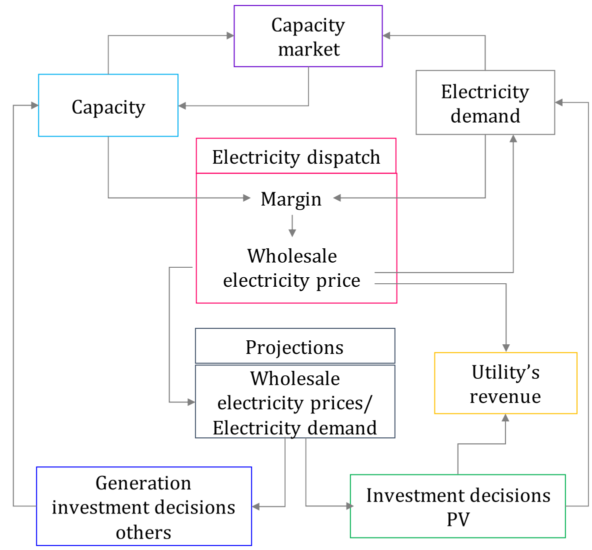


**Fig. 5.** Overview of the SD model.
Source: Own elaboration based on [40].

Installed capacity includes the capacity of rival companies and that of Company A. The complete dynamic hypothesis is shown in Appendix A.

Fig. 5 shows an overview of the model structure, comprising the main components of the model. The model proposed here integrates the dynamic and structural complexities of the electricity industry, such as supply-demand interactions and their effect on investment decisions, which are the key driver of this model. Investment decisions over energy sources can be taken by generators or customers: in the former, generators consider the expected profit among several technology alternatives to invest in large-scale projects; in the latter, customers take into account a cost comparison between LCOE from PV and the electricity tariff in deciding whether to adopt a solar PV system. Though the industry is modelled as a whole, Company A and its corresponding assets are disaggregated from all the other utilities.

Based on the proposed model structure, a formal simulation model was built using the Powersim software, to test the dynamic hypothesis presented in Figs. 3 and 4. This broad model structure, previously used to analyse the British electricity market [40], was adapted and modified to satisfy the aim of this study. A simulation time horizon of 20 years (2015–2035) was considered suitable to study the mid- to long-term effects of the penetration of renewables. The drivers of the model are the investment decision processes relating to power generation, and they depend on: a) tariff formation, b) diffusion of solar PV and c) generation technology choice.

The electricity tariff $EC$ paid by consumers (Eq. (2)) incorporates the following components: generation charge $G$ (also called electricity price in Fig. 4), transmission charge $T$, distribution charge $D$, retail charge $R$, and other charges that incentivise renewable energies and security of supply [56].

$$EC = G + T + D + R + Other \tag{2}$$

PV diffusion follows the Bass model [57] that considers how information disseminated through potential households translates into PV-adoption. Eq. (3) establishes that the adoption rate, $n(t)$, depends on the potential number of adopters, $m$, the cumulative number of adopters at time t, $N(t)$, and coefficients of innovation and imitation, which correspond to $p$ and $q$, respectively [58]:

$$n(t) = \frac{dN(t)}{dt} = p[m - N(t)] + \frac{q}{m}N(t)[m - N(t)] \tag{3}$$

Eq. (4), representing a Logit Model [59,60], establishes the fraction of solar PV adoption, $s_i$, that results from dividing the $LCOE$ solar PV by the sum of this same term and the electricity tariff $EC$, with the $\lambda$

parameter indicating the willingness to choose the PV technology.

$$s_i = \frac{LCOE^{-\lambda}}{LCOE^{-\lambda} + EC^{-\lambda}} \quad (4)$$

The Logit model is also used for establishing the share of investment in large-scale power technologies (e.g. between coal, gas and hydro), by comparing the LCOE indicator for each technology.

This section now turns to discuss some of the main model assumptions that have been considered, regarding the features of the utility and system involved in this research, followed by the presentation of alternative scenarios that have been created to structurally assess feasible *futures* for the electricity industry in the years to come. Finally, the information sources of the model inputs are presented to establish confidence in the model's results.

Some important model assumptions include: i) capacity expansion in non-conventional technologies is undertaken through an investment function that depends on technology indicators; and ii) alternative renewable-based technologies for power generation include: wind, small hydro, biomass, geothermal and, at the residential level, solar PV.

The main assumptions concerning solar PV include: i) adoption of this technology occurs in the residential sector only (although it accounts for about 40% of the country's total electricity demand [61], this represents a considerable underestimate of the total potential); ii) net-metering is in place; iii) this technology does not incorporate battery storage; iv) no new investments are undertaken in distribution network assets; v) the sizes of the PV systems adopted by households remain constant during the simulation period, and range between 1 kW and 2 kW; and, vi) the model does not consider differential tariffs for the different income levels that are prevalent in Colombia.

Scenario-based modelling is helpful when the future is highly uncertain, as has been previously discussed in the context of the problem faced in this paper [49]. The selected scenarios are the result of several experiments conducted in Colombia over recent years, in a series of workshops with managers, engineers, energy specialists, policy makers and so on [62]. The four scenarios shown in Fig. 6 are the result of the permutation of two of the most uncertain drivers of the system: environmental policy and renewable energy costs, which are represented on the $x$ axis and $y$ axis, respectively. Note that renewable energy costs are considered high when they are above those supplied by the electricity grid, or when they are higher than those of competing generation technologies, during the considered period of analysis.

The promotion of solar PV by an awareness-raising campaign has been applied as part of a strong environmental policy, along with a Feed in Tariff (FIT) or an alternative investment subsidy. FIT – commonly implemented worldwide [63] – was assumed to cover 110% of the LCOE. The investment subsidy was assumed to be 100% of the total. A *fragile environmental policy* exists when there is little promotion of solar PV, and both FIT and investment subsidies are absent. Table 2 indicates the cases where FIT and investment subsidies are implemented.

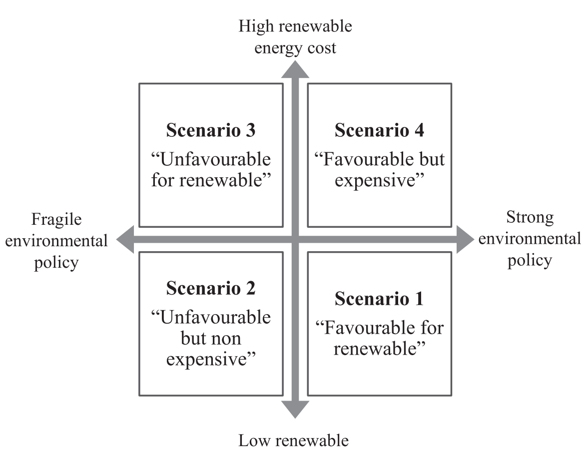


**Fig. 6.** Scenarios for analysing renewable energy impact on a utility.
Source: Own elaboration based on [62].

**Table 2**
Financial incentives applied to each technology during the simulation.
Source: Authors.

| | Fixed Feed-in Tariff | Investment subsidy |
|---|---|---|
| Wind | Yes | No |
| Biomass | Yes | No |
| Geothermal | Yes | No |
| Small hydro | No | Yes |

Lastly, the model uses data from the different Colombian agencies: the Operation and Maintenance (O & M) costs, investment cost, construction time of power technologies, electricity demand projections and power projects in construction, all from UPME [64]; availability factor and load factor of technologies, from XM [53]; average consumption and electricity tariff, from SUI [61]; and, population and number of households, from DANE [65].

## 4. Simulation results

This section discusses simulation runs for the different scenarios considered in this study. First, it analyses the overall impact of renewables on the industry, as utilities are immersed in the corresponding electricity power system; later it discusses this effect on Company A, the utility selected for the case study; and, finally, it assesses an extreme case of high solar-PV penetration.

### 4.1. Impact on industry

This subsection describes the effects of renewables (including residential rooftop PV) on the power industry. Impact indicators for the industry include the wholesale electricity price and share of RES in electricity generation – both obtained through the electricity dispatch module (see Fig. 5). The electricity tariff evolution is shown in Appendix B.

Fig. 7 shows wholesale electricity prices under different scenarios. Initially, prices drop due to the launch of 2400 MW from the Ituango hydropower project (an addition of almost 15% to the installed capacity), which will start operations in two stages between 2018 and 2022. During this period, marginal prices are set by hydroelectric resources; from 2022 onwards, market prices recover in all scenarios as the excess of hydro and renewable supply no longer meets electricity demand and a small share of fossil capacity is needed.

Clearly, a different technology mix leads to different wholesale electricity price patterns; thus, the growth of renewable energy along with hydropower investment produces the lowest wholesale electricity

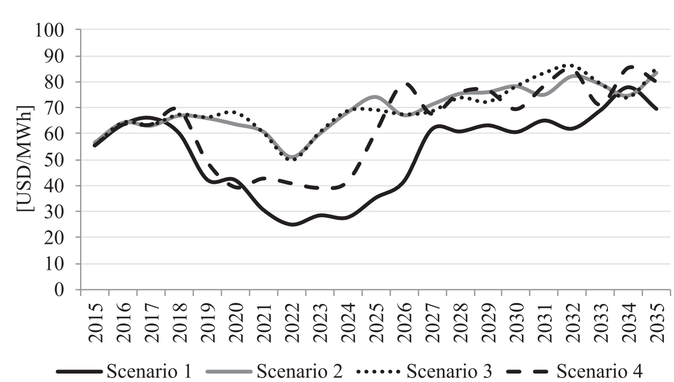


**Fig. 7.** Wholesale electricity price.
Source: Authors.

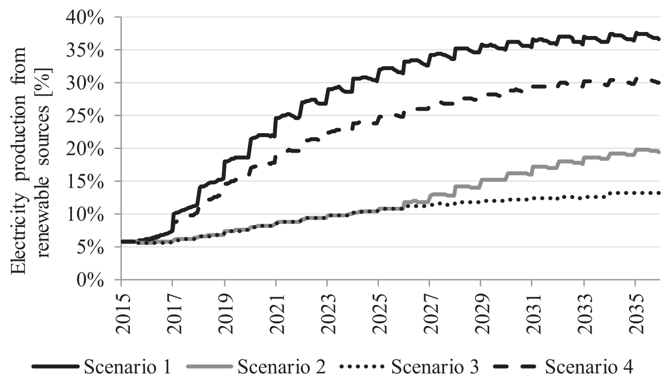


**Fig. 8.** Share of RES in electricity generation.
Source: Authors.

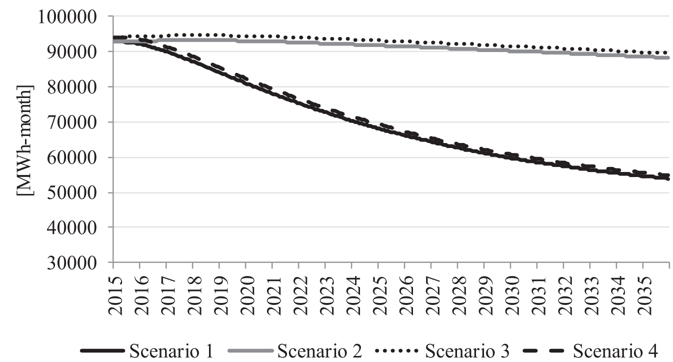


**Fig. 9.** Electricity sales of Company A to the residential sector.
Source: Authors.

price for scenarios 1 and 4, while the lower renewable deployment prompts higher wholesale electricity prices for scenarios 2 and 3 during the simulation period. Wholesale electricity price tends to converge to prices between 60 and 80 USD/MWh by the end of the simulation period (see Fig. 7). Wholesale electricity price shows peaks by the middle of the simulation period, when wholesale price is set by gas-fired plants under scenarios 2, 3 and 4 – these peaks are more noticeable in scenario 4 where greater renewable generation is tied to larger variability. Divestments of gas and coal technologies do not take place as both were granted capacity payments for the purposes of system reliability. Results show how investment in RES reduces the wholesale electricity price due to the merit order effect, as obtained in other studies, such as Rathmann [66].

Fig. 8 shows that the environmentally-friendly policy is more relevant than the cost of renewable energy, for the adoption of renewable technologies. The share of RES in total electricity consumption is projected to reach 35% (4456 GWh/month) by 2035 for the most favourable market conditions and about 16% (1923 GWh/month) under the most unfavourable market conditions (see Fig. 8); solar PV electricity contributes about 13% (1655 GWh/month) to Colombia's electricity supply from 2025 to 2035, under scenarios 1 and 4.

The driver for increases in renewable technology is the environmentally-friendly policy; by 2035, renewables could reach between 15 GW and 20 GW if a friendly environmental policy is implemented (scenarios 1 and 4), while in the absence of such a policy, renewables could reach only between 6 GW and 9 GW (scenarios 2 and 3).

### 4.2. Impact on the integrated utility business

Whereas the previous subsection shows some of the effects of the penetration of renewables in the electricity market, this subsection examines these effects on Company A. As renewables are already reaching competitiveness in all scenarios from the outset of the simulation period, this explains why solar PV expansion makes important progress in scenarios 1 and 4 as well as in scenarios 2 and 3, and there is not much difference between them. The gap between the electricity tariff and LCOE, for solar power, increases in the initial years, thus solar PV reinforces its cost-competitive advantage over grid electricity through the years. The improving cost-competitiveness, along with public policy support for renewables, promotes distributed PV adoption; this leads to a positive feedback effect where self-generation reduces electricity demand, forcing utilities to increase tariffs, resulting in further PV adoption, which is more notable in scenarios 1 and 4 that are characterised by the higher levels of PV adoption (10,600 MW by 2035).

While in scenarios 2 and 3 the residential electricity demand from the grid is reduced as a result of the growing numbers of PV-owners, in scenarios 1 and 4 the residential electricity demand remains almost constant, due to lower solar PV diffusion. Fig. 9 shows similarities in residential electricity sales by the utility Company A, under scenarios 1 and 4, and scenarios 2 and 3, as these scenarios have almost the same amount of solar PV. Additionally, Fig. 9 shows that under scenarios 1 and 4 the simulated volume of residential electricity sales by 2035 was 42% lower with respect to those in 2015; while for scenarios 2 and 3 the volume of residential electricity sales by 2035 was only 5% lower with respect to 2015.

Fig. 10 shows how, under scenarios 1 and 4, the number of PV adopters exceeds the number of non-PV-adopters by the middle of the simulation period, while for scenarios 2 and 3, the number of PV adopters is always lower than the number of non-PV-adopters.

As shown in Fig. 11, profits of Company A decline for all scenarios during the period when the Ituango power plant generation enters the market – from 2018 to 2022. As expected, the reduction in the electricity market price, caused by the expansion of renewables and hydroelectricity capacity, also reduces the profits of Company A from its generation business, as shown in scenario 1. Under scenario 1, the financial loss could be worse for gas power plants; however, its load reduction is compensated by the capacity payment received. As expected, the impact of renewable electricity on the spot market reduces the profits for generators, as stated in results obtained by Sensfuß et al. [20].

Fig. 12 shows the revenues of the utility Company A from its distribution business (which includes the retailing part of the business). Note that revenues behave as profits, given that this is a cap-regulated business. Solar PV erodes the electricity sales of utilities, because self-generation means lost sales, thus for scenarios 1 and 4 the higher deployment of rooftop solar PV (10,600 MW by 2035) leads to lower revenues in comparison with scenarios 2 and 3 (4400 MW of rooftop solar PV by 2035). For these scenarios the effects of solar DG on utilities seem modest, coinciding with Satchwell et al. [67], but a more prominent scenario is analysed in the next section.

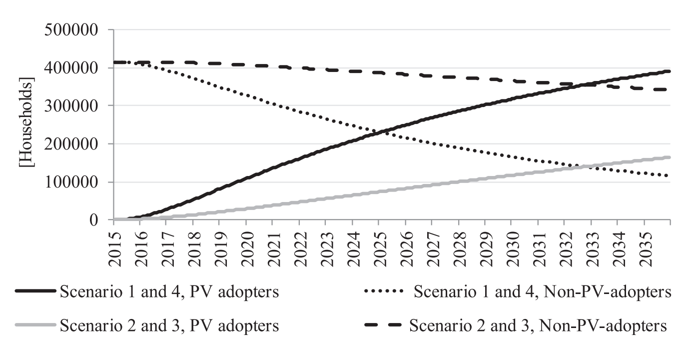


**Fig. 10.** PV adopter vs Non-PV-adopters.
Source: Authors.

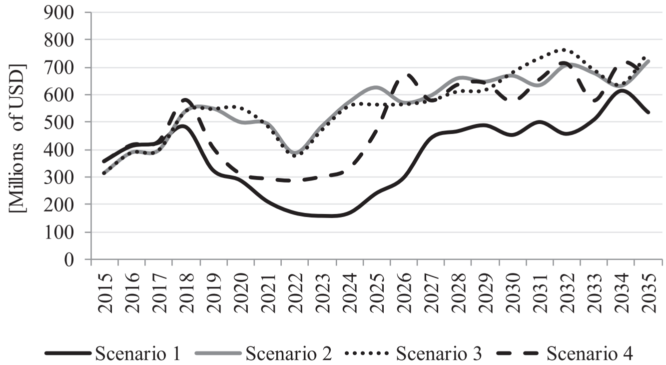


**Fig. 11.** Indicative profits of Company A from its generation business.
Source: Authors.

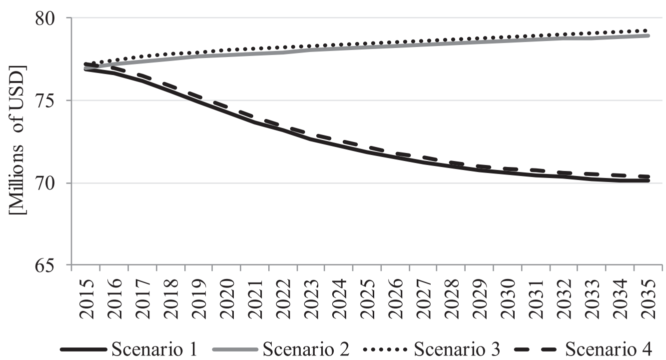


**Fig. 12.** Revenues of Company A from distribution and retail business.
Source: Authors.

### *4.3. Effect of an intensive solar PV deployment policy*

Solar PV capacity for the least and the most favourable scenarios ranges from 4400 MW to 10,600 MW, respectively. In the previous scenarios, each PV adopter has a system size of 1 kW. On average, a household consumes 224 kWh per month. Therefore with a system size of 1 kW the panel would generate 150 kWh per month, (1 kW*5 sunshine hours*30 days). As generation is lower than average consumption, a little energy will be supplied from the grid.

With a system size increase of 50% (1.5 kW) the panel would generate almost exactly the average energy consumption, 224 kWh, reaching about zero net energy; and with a system size increase of 100% (2 kW) the panel would generate 300 kWh per month, so on average 76 kWh per month would be supplied to the grid. Under scenario 1, if each household installs a panel size of 1.5 kW the solar PV deployment would be 15,947 MW. Fig. 13 and Fig. 14 show that for a

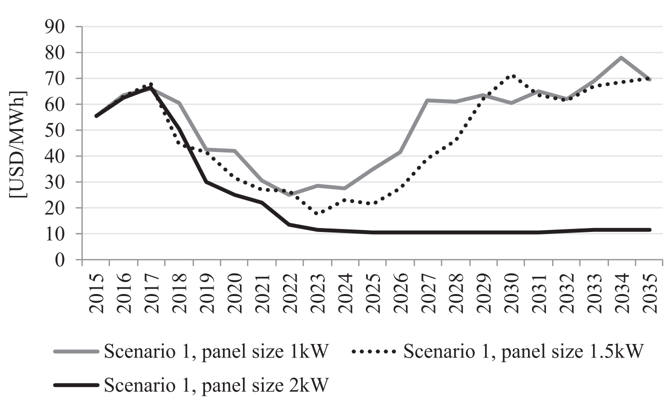


**Fig. 13.** Annual wholesale electricity price for scenario 1 under different levels of PV expansion.
Source: Authors.

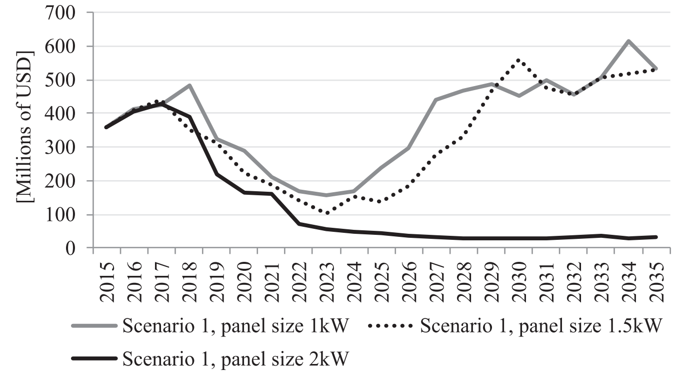


**Fig. 14.** Indicated profitability from the electricity generation business of Company A, for scenario 1 and different levels of PV expansion.
Source: Authors.

panel size of 1 or 1.5 kW, the generation business suffers but recovers by the end of the simulation; for a panel size of 2 kW, the power business would be unsustainable and the installed solar PV capacity would rise to 19,874 MW; as a consequence the wholesale electricity price would be driven down, to remain at the lowest level.

With a system size of 2 kW, self-generation reduces the residential electricity demand to zero in the long run; this pushes grid costs to very high values, which become exponential (see Fig. 15). Similar behaviour is experienced for the electricity tariff, which includes the transmission and distribution charges.

Fig. 16 shows that for scenario 1 with a panel size of 2 kW, the distributor will experience financial difficulties in the long-term, as consumers will be unable to pay the extremely high electricity tariffs; these circumstances would be catastrophic for the retail and distribution business model.

The impact of PV penetration is perceived not only by utilities but also by non-PV-adopters (affected by high energy bills), especially the low-income utility customers. Table 3 shows the financial impact on a lowest income household that is a non-PV-adopter, under different levels of solar PV deployments – the average consumption of a Colombian family from the lowest income level is 134 kWh/month (SUI, 2015), its wage is about US$214 per month. For scenario 1, only 23% of households remain as non-PV-adopters, and the grid tariff for a low income non-PV-adopting family will increase, largely due to distribution-charge growth, to 0.20USD/kWh by the end of the simulation period. Under these conditions the energy expense for non-PV-adopters would be equivalent to 13% of the household income.

If the conditions of scenario 1 are applied but families install a larger panel size, greater energy expense would be triggered for non-PV-adopters, leading to an unsustainable situation for society and the electricity system; for instance, for a panel of average size 2 kW, the

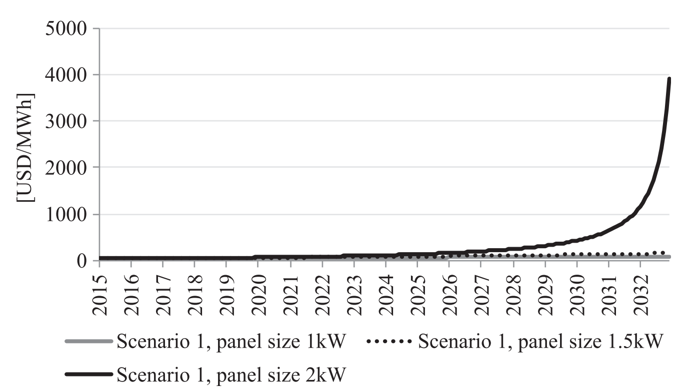


**Fig. 15.** Distribution charge of Company A, for scenario 1 and different levels of PV expansion.
Source: Authors.

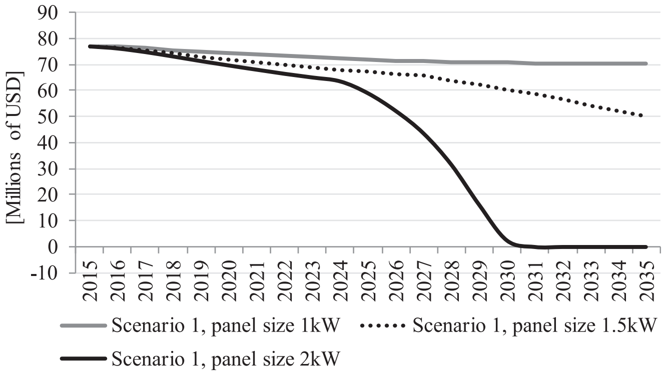


**Fig. 16.** Company A's profitability from electricity distribution and retail business, for scenario 1 and different levels of PV expansion.
Source: Authors.

tariff in 2033 would be 6USD/kWh, and the energy expense, if it could ever reach such a level, would be equivalent to 376% of the family income. In this case, it would be better for residential customers to install a PV system of at least 1.5 kW, to meet their daily average electricity demand, and to protect them from the high grid tariffs when PV systems are not operating. Note that the initial grid tariff in Colombia for the household sector is US 0.13USD/kWh and that even in scenario 3, the most unfavourable for renewables, this increases to US$0.18 (38%). The increase is even higher in scenario 1, where the tariff reaches US$0.20 (54%), when average panel size is 1 kW, or to US$0.30 (131%) when average panel size is 1.5 kW, as shown in Table 3.

Sensitivity analysis is undertaken in this paper by: a) examining different scenarios, b) analysing different sizes of PV systems, and c) considering variations of the parameters $p$ and $q$ in the Bass Model (to reduce the PV adoption by households). A further sensitivity analysis is conducted when considering PV adoption among small companies, as shown in Table 4. When only 30% of residential customers adopt solar PV systems by 2035, the tariff in 2035 would be 0.19 USD/kWh, and the energy expense would be equivalent to 12% of the family income. However, if along with 30% of residential customers, a further 49% of small companies adopt PV systems, the energy expense for non-PV-adopters would reach 108%, as indicated in Table 4.

Tables 3, 4 establish a limit to solar PV growth that could lead the whole system to collapse. The solar PV growth would be so great that the recovery of fixed costs by utilities would be impossible. Because of this, utilities could view solar DG as a threat to their financial sustainability; at the same time, however, this threat also represents an opportunity for changing their business model, for example some utilities have moved into *clean* electricity supply, such as E.ON and RWE in Germany. For validation purposes, Appendix C compares the utility Company A with the utility industry as a whole, showing the consistency of simulated results. From a systems-modelling perspective, the paper meets its objective by assessing the potential impact of RES on the integrated utility, the industry and related environmental issues, while also testing the utility death spiral hypothesis.

**Table 4**
Financial impacts on non-PV-adopters of differing solar PV deployment with different assumptions.
Source: Authors.

| | Scenario 1 panel size of 2 kW[a], dates at 2035 | Scenario 1 panel size of 2 kW with special conditions[b], dates at 2035 |
|---|---|---|
| Solar PV cumulative installed capacity[*] | 9030 MW | 19,843 MW |
| Energy consumption by household | 134 kWh | 134 kWh |
| Grid Tariff (USD) | 0.19 USD/kWh | 1.73 USD/kWh |
| Expense on electricity by a non -PV-adopting household | 134 kWh x 0.19USD/kWh =25USD | 134 kWh x 1.73USD/kWh=232USD |
| Monthly income of lowest income household (USD)[c] | 214USD | 214USD |
| Share of energy expense with respect to income | 12% | 108% |

[*] Parameter values of the Bass Model are $p$ = 0.02 and $q$ = 0.03.
[a] Under this scenario 30% of households adopt solar PV systems by 2035.
[b] Under this scenario 30% of households and 49% of small companies adopt PV systems by 2035.
[c] Minimum income received by an employee.

## 5. Conclusions and policy implications

This paper reaches conclusions on a variety of issues regarding the valuation of the effect of the penetration of renewables on the social, economic and environmental aspects of the electricity industry, with particular emphasis on utilities. The paper provides insights into policy analysis, contributing to a better understanding of the short- and long-term effects of the penetration of renewables (roof-top solar) on the utility business and on the industry as a whole. Other lessons include insights into energy and environmental policy. The objective of this paper has been achieved regarding the impact of renewables on the integrated utility business, the industry and environment-related issues.

First, on the utility-death-spiral issue, two factors contribute to the acceleration of the adoption of solar PV in the household sector, with negative consequences on the utilities sector: a) the declining energy consumption caused by increases in domestic PV generation, and b) the need of utilities to increase transport tariffs to customers. The effect of the size of PV system was analysed for the Colombian case and the

**Table 3**
Financial impacts on non-PV-adopters of different solar PV deployment.
Source: Authors.

| | Scenario 1 panel size of 1 kW, dates at 2035 | Scenario 1 panel size of 1.5 kW, dates at 2035 | Scenario 1 panel size of 2 kW, dates at 2033[a] |
|---|---|---|---|
| Solar PV cumulative installed capacity[*] | 10,602 MW | 15,947 MW | 19,874 MW |
| Energy consumption by household | 134 kWh | 134 kWh | 134 kWh |
| Grid Tariff (USD) | 0.20 USD/kWh | 0.30 USD/kWh | 6 USD/kWh |
| Expense on electricity by a non-PV-adopting household | 134 kWh x 0.20 USD/kWh=27USD | 134 kWh x 0.30 USD/kWh=40USD | 134kWh x 6USD/kWh=804USD |
| Monthly income of lowest income household (USD) | 214USD[b] | 214USD | 214USD |
| Share of energy expense with respect to income | 13% | 19% | 376% |

[*] Parameter values of the Bass Model are $p$ = 0.09 and $q$ = 0.10.
[a] These are the final values; beyond year 2033 the electricity system collapses.
[b] Minimum income received by an employee.

results suggest that when households are over-installed, i.e. when PV system size is greater than 1.5 kW, the distribution tariff rises to unbounded levels, which may intensify the utility death spiral.

The industrial and commercial sectors have not been included in the analysis. Therefore, the simulations largely underestimate the intensity and the speed of the full effect on electricity utilities that results from the potential penetration of rooftop PV in the power market.

The results from this paper clearly underestimate the effects that the penetration of all DG technologies might inflict on the utility industry, as many of these concerns have not been considered in the analysis. Although this is a conceptual discussion, it is not based on only one single case as: a) simulation of both demand reductions from the grid as well as electricity price hikes were observed for the industry as a whole, b) similar results, not reported, were obtained for a different company and c) there are early signs of the modelled effects in countries such as Germany. Beyond all the above, policy lessons may also be drawn from consideration of the equity principle among electricity customers.

Second, regarding the impact of renewable penetration on the industry, results from simulation of the Colombian case show that the wholesale electricity price drops due to the inception of 2400 MW (over 15% of total capacity) from the Ituango hydropower project, in addition to the expansion of renewable energies. Note that the addition of renewables and some hydro power capacity to the Colombian system will replace the most expensive marginal-cost plant, and this in turn will induce lower wholesale electricity prices – the merit-order effect. Further, high solar PV penetration could increase grid vulnerability to all customers because grid investment would not be feasible as a result of declining sales and profits.

Third, with respect to the impact of renewable penetration on utilities: the merit-order effect represents a threat to the generation business, which will experience a profit reduction; in the case of a death spiral this is clearly a threat for utilities because this reinforcing cycle means a drop in terms of sales. In addition, under conditions of high renewable penetration, the generation and retail business is the most disadvantageous in the short-term while it is the distribution business that will suffer most in the long-term. Although it is not studied in this paper, an alternative for utilities to avert the death spiral could be to adapt their business models to the new circumstances imposed by the growth of DG.

Fourth, on the environment-related issues: this paper concludes that an environmental policy is more effective at promoting renewable deployment than the reduction of renewable generation costs; this is more notable for solar PV, which has already reached grid parity in a great number of regions. Scenarios with no commitment to an environmental policy lead to more thermal capacity in place and low expansion of renewables; as expected, if no environmental policy was to be applied then a scenario with lower renewable-generation cost is better than a scenario with high generation cost, in terms of the diffusion of renewables.

Fifth, for the Colombian case: an important part of this paper was dedicated to showing and analysing the death spiral of the Colombian electricity industry, particularly for Company A, under conditions that may lead to the collapse of the system. Though the case discussed in the paper is country specific, some of the findings may have similar implications in other parts of the world.

Lastly, further research could explore how simultaneously to take advantage of renewable energies while averting their undesirable effects.


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## Appendix A. Integrated dynamic hypothesis

Fig. A.1 integrates the dynamic hypothesis depicted in Figs. 3 and 4, with additional variables added to provide a deeper insight into the modelling aspects.

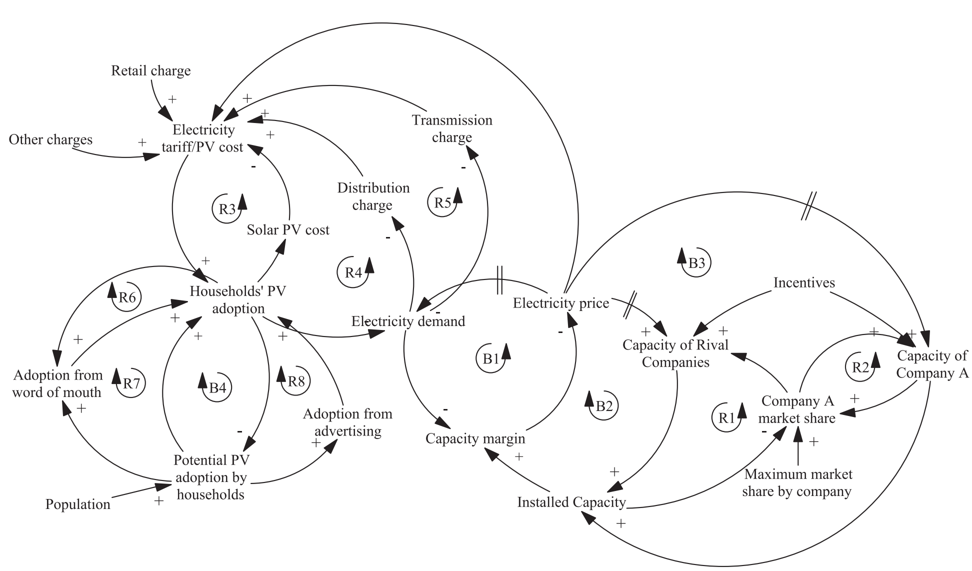


**Fig. A.1.** Dynamic hypothesis for the diffusion of solar PV systems and the electricity market.
Source: Authors.

## Appendix B. Electricity tariff evolution

Fig. B.1 shows the electricity tariff evolution for scenarios 1–4, posed in Section 3. In general, scenarios with higher renewable penetration have a higher electricity tariff for consumers as the reduction of wholesale electricity price caused by generation of renewable energies does not compensate the increase in network costs induced by rooftop solar PV generation. The net effect of rooftop solar PV in the current electricity sector will mean increases in electricity tariffs.

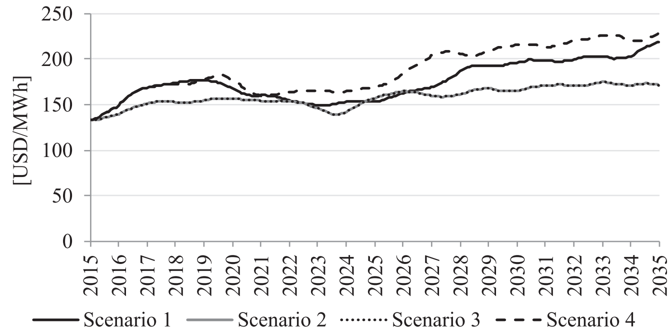


**Fig. B.1.** Electricity tariff evolution.
Source: Authors.

## Appendix C. Simulating an alternative company

This appendix compares the results obtained for Company A – the profitability for the generation and distribution business – with the results obtained for the whole industry (Castaneda et al. [68]). The latter study analyses simulations for the whole electricity utility industry as a unit. Table C.1 shows similar results for the case where the average 2 kW PV system is installed in each household.

**Table C.1**
Comparison for validation purpose.
Source: Authors.

| | Company A Scenario 2 kW | Utility industry Scenario 2 kW |
|---|---|---|
| Wholesale electricity price [USD/kWh] | 0.012 | 0.010 |
| Grid Tariff (USD) [USD/kW] | 6 | 7 |
| Share of energy expense with respect to income | 376% | 438% |

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