UNIVERSIDAD NACIONAL DE COLOMBIA

Framework for assessing environmental friendly strategies with the support of simulation

Marco para la evaluación de estrategias ambientalmente amigables con el soporte de simulación

Doctoral Thesis

Author

Mónica Castañeda Riascos

Supervisors

Carlos Jaime Franco, Isaac Dyner

Universidad Nacional de Colombia – sede Medellín

Facultad de Minas

Departamento de Ciencias de la Computación y la Decisión

Medellin, Colombia

2017

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.

This thesis studies: (i) the potential impact of renewable energy sources (RES) on electricity systems −merit order-effect and revenue erosion caused by distributed generation −, particularly, on the generation and distribution businesses, and (ii) measures to lead with the possible consequences of investments in renewable energy sources. For this purpose, a fairly detailed and integrated supply and demand-based system dynamics model has been built. 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. Simulation runs suggest that subject to policy and economic circumstances, 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".

Furthermore, strategies to address death spiral were simulated, results indicate that under certain conditions it is possible to attain a balance between social welfare and the aversion of the utility death spiral through systemic interventions.

Keywords Electricity utilities; renewables; death spiral; system dynamics, distributed generation; solar PV

Resumen

El cambio tecnológico de sistemas basados en combustibles fósiles a energías renovables ha sido promovido por los gobiernos con el propósito de descarbonizar la industria eléctrica. Sin embargo, el rápido progreso de la tecnología ha provocado cambios perturbadores que transforman las estructuras del mercado. Las empresas de electricidad, en particular aquellas que usan combustibles fósiles, están cambiando de su situación estable y previsible para enfrentar los retos impuestos por empresas que ofrecen otros servicios. En este nuevo entorno, la industria se beneficiará de la previsión sectorial de mediano y largo plazo.

Esta tesis se estudia: (i) el impacto potencial de las fuentes de energía renovable (RES) en los sistemas eléctricos (orden de mérito y erosión de los ingresos de las empresas debido a la generación distribuida), particularmente, en los negocios de generación y distribución; y (ii) medidas para lidiar con las posibles consecuencias de las inversiones en fuentes de energía renovables. Para ello, se ha construido un modelo de dinámica del sistema basado en la oferta y la demanda, bastante detallado e integrado. En el modelo desagrega el sector de los hogares, que puede generar una parte significativa de su electricidad utilizando energía solar distribuida. Esto se ilustra mediante el análisis de una empresa de servicios públicos que se dedica a los negocios de generación y distribución en el mercado eléctrico colombiano. Las corridas de simulación sugieren que, dadas ciertas circunstancias políticas y económicas, la generación solar distribuida es una gran amenaza para las empresas de electricidad. Mientras que el negocio de generación es el más afectado en el corto plazo, el negocio de distribución es el más impactado en el largo plazo, y conjuntamente pueden inducir la "espiral de la muerte" de la empresa.

Además, se simularon estrategias para abordar la espiral de la muerte, los resultados indican que bajo ciertas condiciones es posible lograr un equilibrio entre el bienestar social y la aversión de la espiral de muerte de las empresas a través de intervenciones sistémicas.

Agradecimientos \ Acknowledgments

There are many people who helped me directly or indirectly to accomplish this work, for which I am very grateful. I would like to express my gratitude towards them all in my own language, because I feel that by doing so my words will be more honest.

Le doy gracias a mis padres Francisco e Ivonne por apoyarme en esta aventura, porque su constancia y determinación me han inspirado a trabajar más y luchar por conseguir mis metas. A mis hermanos, Andrés, Daniel y Marcela, por animarme a hacer el doctorado. A Santiago, por acompañarme en mis jornadas de estudio con su ternura.

Le doy gracias a Sebastián por sus valiosos aportes en la conceptualización y construcción del modelo, por brindarme su amistad en los momentos que más la necesitaba. A Maritza por compartir su conocimiento, porque sus aportes fueron fuente de inspiración de este trabajo.

Agradezco a mis amigos brasileños de la Universidad de Rio de Janeiro, su director Nivalde y los investigadores Daniel, Lorrane y Francesco quienes muy amablemente me recibieron en su grupo de investigación Gesel, donde realice mi pasantía. También, agradezco a Judith porque acepto recibirme para completar mi pasantía en el Imperial College, y por sus valiosos aportes a esta investigación.

Gracias a Hassan por sus valiosos consejos y por ser un aliado en este proceso. Gracias a Isaac por creer en mi investigación. También a Carlos Jaime por su retroalimentación y aportes.

En cuanto a las instituciones que me ayudaron, estoy agradecida con Colciencias, la Universidad Nacional y EPM. Colciencias financio mi doctorado durante 3 años y medio, en tanto la Universidad Nacional y EPM financiaron algunos de los congresos en los cuales pude compartir mi trabajo con la comunidad académica. Por último, le doy gracias a Dios por permitirme vivir esta experiencia.

Contents

List of figures

List of tables

Chapter 1. Introduction

1.1 Motivation and challenges

There is a global trend in renewable investment, governments are increasingly committed to reach a low-emission economy. For instance, developing and emerging economies have taken a leading role in the growing adoption of renewable targets, from 2005 to 2015, the number of countries committed with renewables pass from 43 to 164 (Irena, 2015) (See also Error! Reference source not found.).

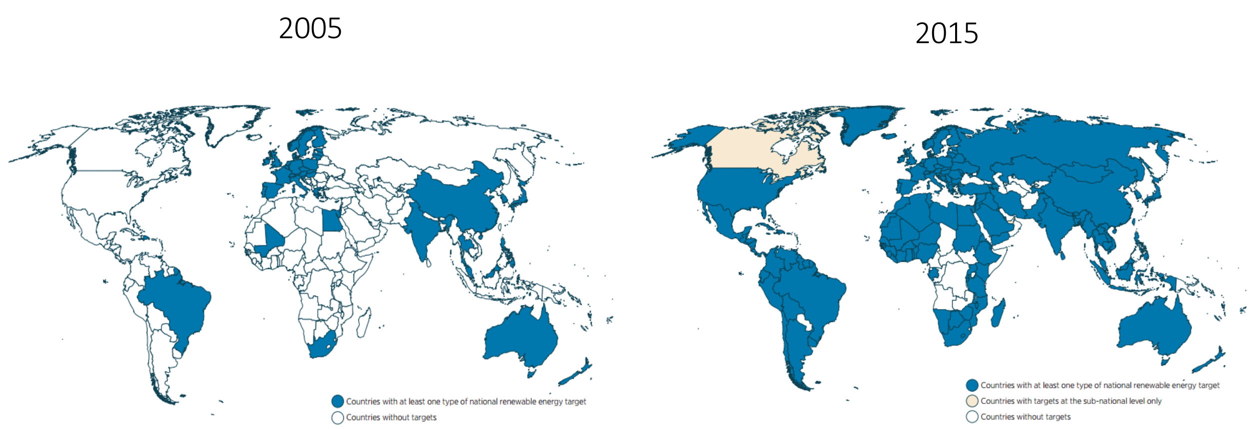

Figure 1. Global map of national renewable energy targets of all types, 2005 vs 2015.

Source: Irena (2015).

In 2015, 61% of new power capacity added globally correspond to renewable energies, demonstrating that, renewable power technologies are currently an important option for expanding electricity infrastructure around the world (Irena, 2017). Renewable technologies such as onshore wind and solar PV are penetrating swiftly in several geographic areas, worldwide. In 2015, global renewable power generation increased about 9.3% over 2014, most capacity additions were in wind and solar photovoltaic (PV), together they account about 77% of all renewable power capacity added in 2015 (147GW) (Ren21, 2016).

In contrast, stricter limits on pollutants threats coal power plants in Europe. Also to the Fukushima disaster some European countries have begun closing the country's ageing nuclear reactors or banned the construction of new reactors (Tveten et al., 2013)

Learning effects make renewable power technologies more atractive. Indeed, the average Levelised Cost of Electricity (LCOE) from solar PV could fall by as much as 59% by 2025, while onshore and offshore wind is expected to drop by 26% and 35%, respectively (Taylor et al., 2016). In addition, these technologies have already reached grid parity in a great number of regions (Breyer & Gerlach, 2013).

The cost reduction for renewable power technologies has incentivized distributed generation based on renewables (Deloitte, 2015). Distributed Generation (DG) is defined as a small-scale electricity generation, not centrally planned or dispatched, located near to the point of consumption, usually connected to the distribution network (Pepermans et al., 2005). DG allows customers to consume and produce energy, i.e., become "prosumers" (Bonbright et al., 1961).

European countries are first in the world developing DG, e.g., Denmark, Finland and Netherlands have an important share of DG from total generation (Gischler & Janson, 2011). While in Latin America, Mexico and Chile stand out (Gischler & Janson, 2011). The development of DG poses opportunities, yet also challenges for policy makers. Some challenges include increasing uncertainty in distribution grid flows and increasing volatility of net demand, local over-voltage or loading issues on distribution feeders, among others (EPRI, 2014).

Additionally, DG technology, particularly when based on solar photovoltaic PV, may be inconvenient to traditional business models of utilities, as costs have been showing swift reductions in recent years (Costello & Hemphill, 2014; Bronski et al., 2014); and these have also pressed further losses to utilities in terms of customers, sales and profits (EPRI, 2014; Satchwell et al., 2015a).

A death spiral for utilities may occur as a reduction in the cost of solar PV sparks the adoption of solar PV panels by households (Castaneda et al., 2016); this, combined with the learning-curve effects, reduces the costs of solar PVs, incentivizing PV adoption. Note that the 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).

Consequently, it is neccesary to change cost structures of Distributor Network Operators and rethink the design of network charges (Pérez-Arriaga et al., 2013). However, under the right regulation and market design DG can be exploited to establish a more efficient and cleaner electricity market (Pérez-Arriaga et al., 2013).The transformation process towards a green and decentralized power system must be reached through optimal energy policies that ensure the energy-political triangle, i.e., a clean, secure and competitive energy future (Röpke, 2013).

Yet, electricity generation from renewable energies could also provide opportunities to electricity companies (Wainstein & Bumpus, 2016; Funkhouser et al., 2015). For example, in Germany, EON, RWE and NRG explored new arenas in solar business models (Kungl, 2015); similarly, some U.S utilities have invested in community solar project such as Sacramento Municipal Utility and Tucson Electric Power (Coughlin et al., 2011).

Two forces will lead to the unavoidable transition to renewable energy sources. The first force is that renewable energies are key to fighting climate, the second force is the ongoing depletion of the world's oil, coal and natural gas resources (Heinberg & Fridley, 2016).

Some countries are moving faster than others to a cleaner and decentralized power system, but undoubtedly all of them will reach this transformation. Regulator and electricity utilities face a variety of uncertainties in predicting the effect of renewable energies development, which hinders their long-term planning. This raises following research questions:

- What are the potential impacts of renewable energy sources (RES) on electricity systems, specifically on the generation and distribution businesses?
- 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?
- Can simulation be of any help to support corrective actions that benefit the technology transition?

Other key questions emerge with respect to the traditional utility business models:

- What impact will solar DG have on electricity companies?
- What opportunities may exist for electricity companies from new business model?
- Can new business models cover the potential losses in electricity companies caused by solar energy?
- Can solar companies be financially sustainable? Which is the best business model for end-users and solar companies to use?

This research aims at answering earlier questions, adding insights to the analysis of the long-term effects of renewable energies on stakeholders. It is applied a System Dynamic (SD) modelling approach. SD is a powerful tool to deal with complex system and policy resistance, this method has been widely used in the field of energy policy and electricity-related (Leopold, 2015). Power systems involve dynamic complexity, i.e., large number of variables and parameters as well as feedbacks, inter dependencies, delays and long-term fluctuations (Pereira & Saraiva, 2013). And SD is suitable to capture these dynamics.

Thus, within the multi-faced aspects of long-term effects from renewable energies on key electricity industry stakeholders, two areas have been identified in this thesis as being of interest to tackle the research problem faced here:

- A systemic view of the socio-economic effects of renewable energies on the power industry, utilities and customers.
- A systemic view of the strategies to adapt to the transition toward a decentralized power industry.

First area corresponds to specific objectives 1 and 2. Second area corresponds to specific objective 3 and 4, which are explained in subsection **4.1**.

1.2 Outline of the thesis

The thesis is structured in four main parts. The first part contains chapter 2 to 4 and mostly deals with theoretical topics regarding the power industry transition toward a cleaner and decentralized paradigm and the research gap. The second part describes in chapter 5 the simulation model built to fill the gap along with its validation process, while, the third part, including chapter 6, uses the simulation model to assess deeply the Colombian case study, and explores the Brazilian and the UK case studies. The fourth part contains chapter 7 and provides the conclusions and future works. The chapters are briefly described below.

Chapter 2 reviews the effect of renewable investment on power market, particularly on utilities (power generators and distribution network operators), renewable energies reduce the wholesale price (merit-order effect) and distributed solar PV may reduce the energy sales of utilities leading to a vicious cycle (death spiral).

Chapter 3 reviews the measures to face the transition toward a cleaner and decentralized power system such as rate design reform, lower compensation to energy exported to the grid, new business models and others. The strategies adopted by utilities are based on these measures and are also reviewed at the end of the chapter.

Chapter 4 addresses the contribution of the thesis on the research topic after providing an exhaustive literature review. This contribution is to develop a systemic approach of the impact of renewable investments on utilities, identifying the potential threats/opportunities and designing strategies to face different scenarios.

Chapter 5 describes the simulation model used and the validation process. The simulation model passes successfully the validation tests, which means that it is adequate to reach the objective of this thesis.

Chapter 6 describes the Colombian electricity market. After simulation runs the impact of renewable investment on a Colombian utility and the power industry is shown. Results suggest that distributed solar

PV represents a high risk for utilities, which motivates to modify the model to treat the utility as a whole unit. This modification allows to analyze the impact of different measures to face the transition.

Chapter 7 concludes the thesis and suggests the future possible areas of extending and continuing the work.

Part I. Global trend in renewable investment

Chapter 2. Effects of renewables on power markets

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 (Bacon & Besant-Jones, 2001; Newbery, 2002a). 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 (Keay et al., 2013; Pollitt & Haney, 2013). Under these conditions, renewable energy is becoming a political priority of governments around the world, electricity utilities face both a rapid technological transformation and regulatory uncertainty (Richter, 2012).

2.1 Renewable energies and distributed energy resources

Renewable technologies such as onshore wind and solar PV are penetrating swiftly in several geographic areas, worldwide (Ren21, 2016). Wind and solar PV power penetration levels continue to increase in the last years (See Error! Reference source not found. **and**Error! Reference source not found. **Figure *3***). 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) (Ren21, 2016). In Latin America, the top three wind power by 2015 were: Brazil (8.7 GW), México (3 GW) and Chile (0.9 GW) (GWEC, 2017). In the same region, the top three solar PV power countries were: Chile (848 MW) and Mexico (282MW).

This increase in renewable installed capacity is also tied to reduction in power generation costs. For example, the global average generation costs for new solar plants has been reduced about a 66% from 2010 to 2015 (IEA, 2015). By 2025 the average levelised cost of electricity (LCOE) of solar PV could fall by 59%, while onshore and offshore wind is expected to drop by 26% and 35%, respectively (Taylor et al., 2016).

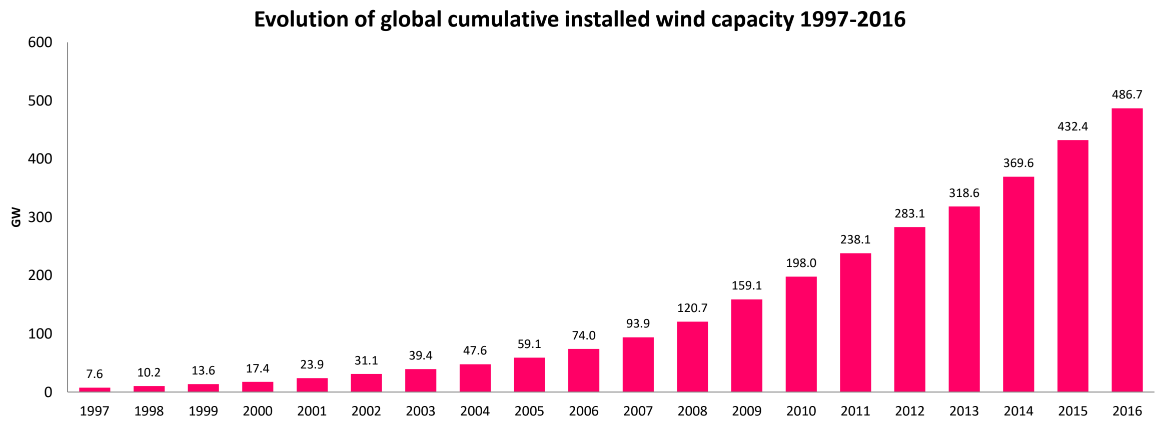

Figure 2. Global cumulative wind installed capacity, from 1997 to 2016.

Source: GWEC (2017).

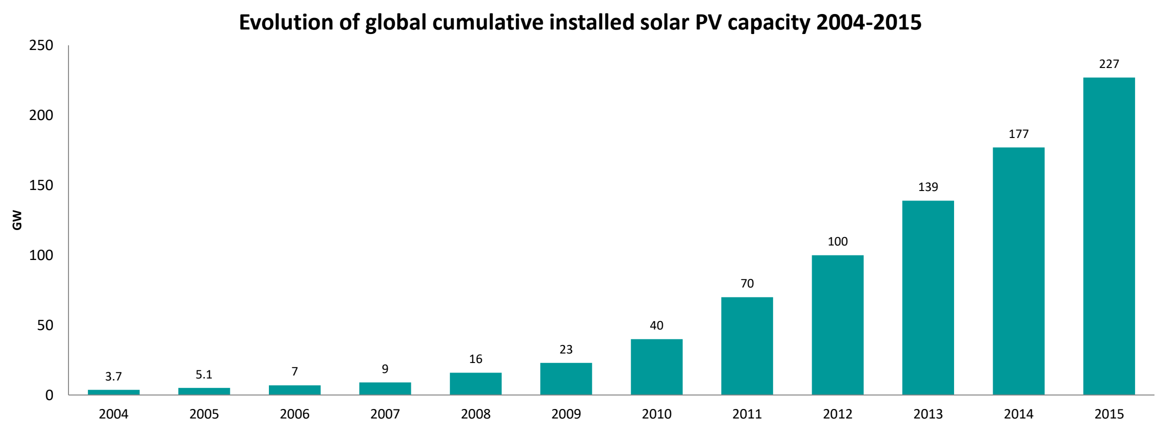

Figure 3. Global cumulative solar PV installed capacity, from 2004 to 2015.

Source: EPIA (2014) and Ren21 (2016).

Figure 4 presents the total installed costs of onshore wind farms for 12 different countries (Brazil, Canada, China, Denmark, France, Germany, India, Italy, Spain, Sweden, the United Kingdom and the United States). The reasons for cost reduction of wind power are: the growth in economies of scale, greater competition among suppliers, technological innovation, improvements in logistical chains and streamlined administrative procedures (Irena, 2016).

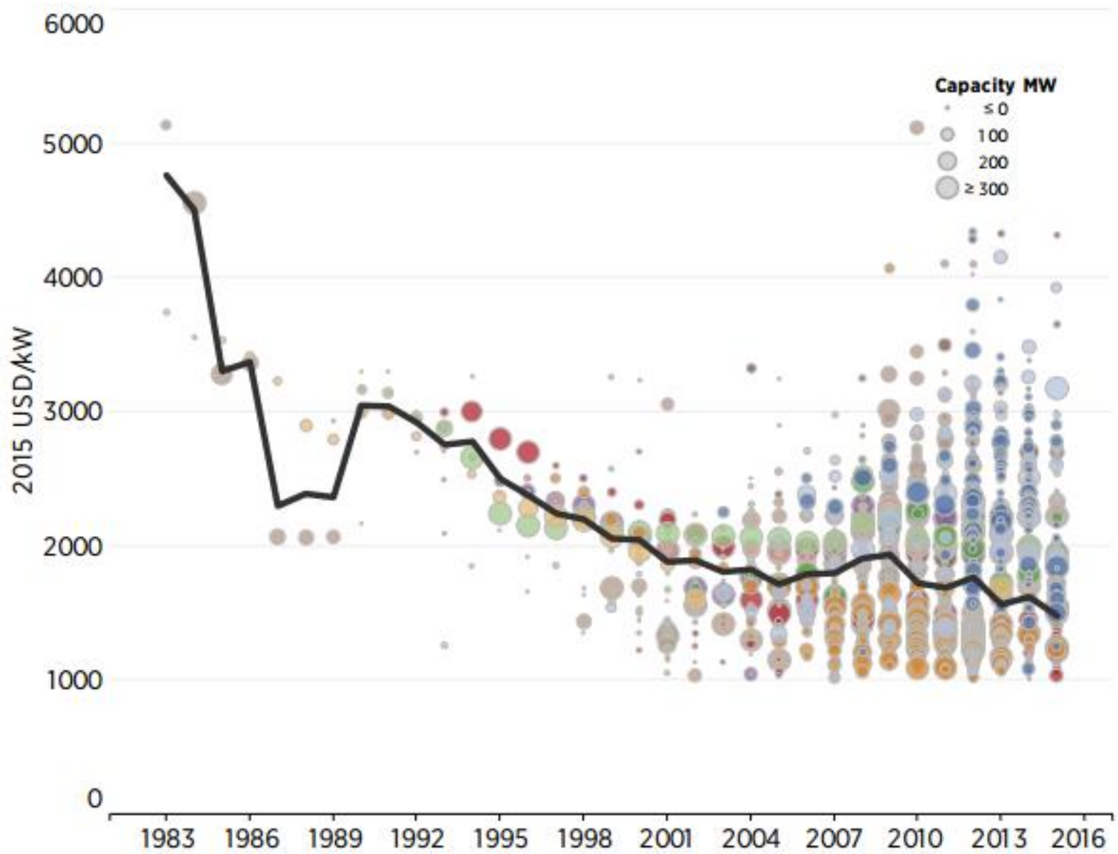

Figure 4. Total installed costs of onshore wind projects by country, 1983-2014.

Source: Irena (2016).

Learning rate for solar PV modules is very high, about 18% to 22%. Solar PV modules have also shown rapid deployment, was about 40% growth in cumulative installed capacity for 2012 and 2013, and about 30% growth in 2014 and 2015. As every time, the global cumulative PV capacity is doubled, module price is reduced by the learning rate (18% to 22%). These factors resulted in PV module prices drop to 80% between the end of 2009 and the end of 2015. The prices have declined slowly between 2010 and 2016 (Irena, 2016) (See **Figure 5**). In general, most renewable energy technologies have experienced cost decline an important technical advance would lead to further cost reductions. Historically, it has been demonstrated that renewable investments are tied to long-term cost reductions, therefore, further cost reductions are expected (IPCC, 2011).

Additionally, due to their greater potential for cost reductions of renewable energy technologies, it is expected that these technologies can successfully compete with conventional technologies at some time in the future; however, as some renewable technologies are more affected by intermittency and seasonality, the problem of integrating successfully renewable energies into traditional electricity planning model is key (Wu & Huang, 2014).

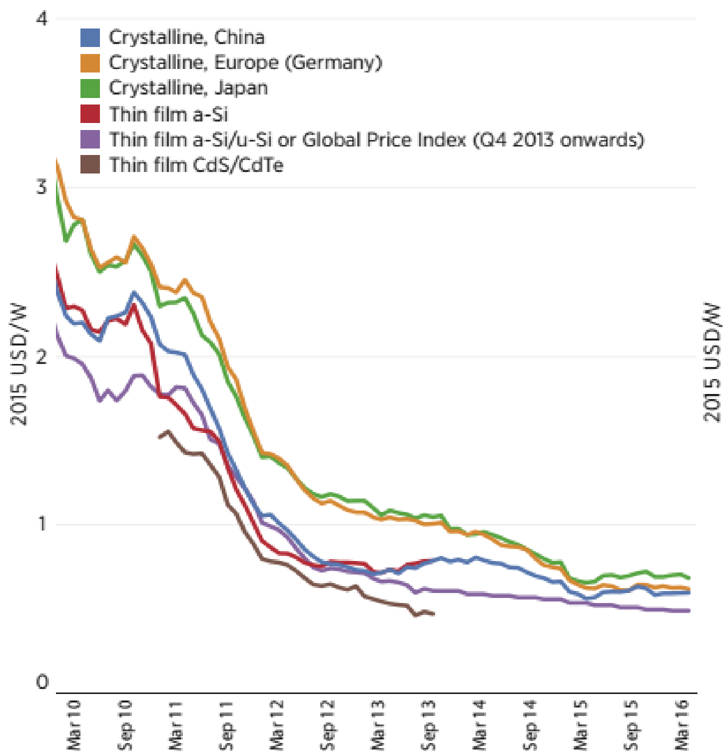

Figure 5. Global PV module price trends, 2009-2016

Source: Irena (2016).

Globally, electricity production should become less carbon intensive in order to reduce greenhouse gas emissions. The transition toward a low-carbon energy system is receiving a lot of attention, because the challenges and changes that it imposed on society (Garcez, 2017). As first industrial revolution was based on coal and steam engine, second industrial revolution was possible by petroleum, the internal combustion engine and mass electrification. The third industrial revolution may include: renewable energy, distributed generation, electricity storage, smart grid and electric vehicles (Rifkin, 2015). Some of these technologies are included in Distributed Energy Resources (DER), that covers distributed generation, local storage, electric vehicles and demand response (Ruester et al, 2014). DERs refer to energy supplies directly connected to medium voltage (MV) or low voltage (LV) distribution systems, instead of the bulk power transmission systems (Akorede et al., 2010).

This research is mainly focused on some of DER technologies. Specifically, Distributed Generation (DG), which is defined as a small-scale electricity generation, not centrally planned or dispatched, located near to the point of consumption, usually connected to the distribution network (Pepermans et al., 2005). DG can be categorized according to the power produced as: micro distributed generation (1 Watt<5 kW); small distributed generation (5 kW<5 MW); medium distributed generation (5 MW<50 MW); and large distributed generation (50 MW<300 MW) (Ackermann, 2001). Micro distributed generation is also called micro-generation systems and is designed to produce electricity in households (EECA, 2010).

This research studies DG based on renewable technologies, particularly solar PV. Since from this research the role of renewables in the pathway towards decarbonization is assessed. Renewable projects can be categorized as (Richter, 2012): Customer-side renewable energy and Utility-side renewable energy. The former refers to projects located on customer's property (DG), with a size of few kW to 1MW based on technologies such as photovoltaic, solar thermal hot water, CHP micro power, geothermal heat pumps, and micro wind turbines. Though, it is necessary to clarify that DG can be used at community scale generating from few hundred kW to few MW of electricity, or at household scale (micro-generation) to produce 1 to 4 KW of electricity (El-Khattam & Salama, 2004).

2.2 Renewable effects on power markets

According to Schleicher-Tappeser (Schleicher-Tappeser, 2012), 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" (Christensen, 1997). 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 (Sioshansi, 2014). Regardless of the similarities with those cases, renewable energies are certainly transforming electricity markets (Haas et al., 2013). 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 to 80 GW (EPRI, 2014).

For studying the effect of technology transformation on the 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 (Schmidt et al., 2016). Thus, this research considers the Colombian electricity market, which is characterised by a high share of hydropower resources combined with some thermo-power dependence.

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.

2.2.1. Impacts on the electricity generation business

Though renewable energies have great potential and bring 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 (Ortega-izquierdo & Del Río, 2016). 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 **Figure 6**), and inducing a low wholesale electricity price (Tveten et al., 2013; Sensfuß et al., 2008) . This may result in lower profits to the incumbent electricity generation business with stranded assets.

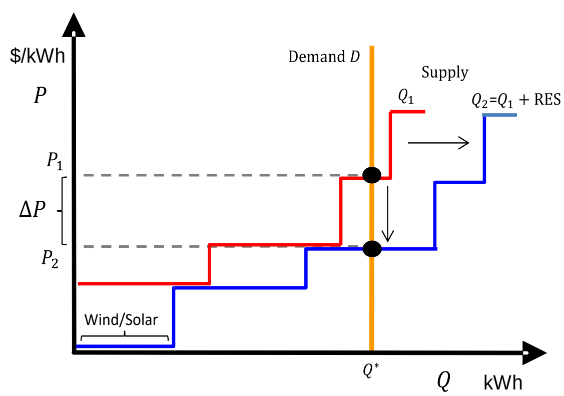

Figure 6. Decrease of power price due to additional Renewable Energy Sources (RES) in the supply curve (merit-order effect).

Source: Authors.

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 (Cai, Adlakha, Low, Martini, & Chandy, 2013) and a reduction in the marginal electricity price (See **Figure 7**).

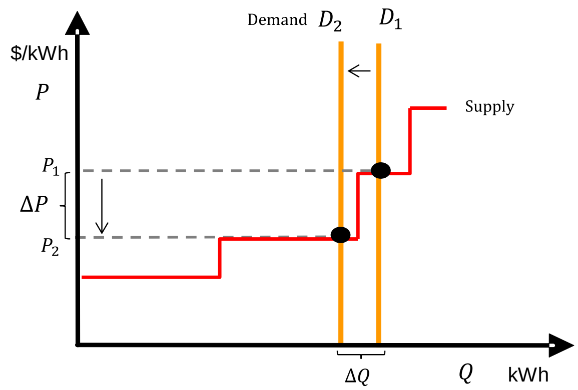

Figure 7. Power price formation by reduction of electricity demand due to Distributed Generation (DG).

Source: Authors.

In the presence of renewables, it is important to consider 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 (Jónsson et al., 2010; Sáenz de Miera et al., 2008; Tveten et al., 2013; Ortega-izquierdo & Del Río, 2016). 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 (Ciarreta et al., 2014; Clò et al., 2015). 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 (EON, 2014). The wholesale electricity price reduction due to renewable energies implies another problem, the "missing money" problem, it consists in the scarcity rents reduction which are embodied in price spikes (Cepeda & Finon, 2013).

Furthermore, some argue that environmental friendly policies to support renewables tend to increase cost of electricity generation, because conventional technologies are the cheapest technologies (Vogel, 2009). However, conventional technologies have also the highest CO2 emissions, and renewable technologies are progressing to become cost-competitive. On one hand, some argue that renewable technologies reduce the daily market price due to merit order effect; on the other hand, some argue that these technologies imposed a high cost on the public support scheme (Ciarreta et al., 2014). If renewable technologies are beneficial or harmful for power system depends on power market circumstances, it could occur that greater renewable energy deployment could even reduce final electricity price, compensating the cost of renewable technologies (Sáenz de Miera et al., 2008).

2.2.2 Impacts on integrated utility business

The greatest threat from DG development is its reinforcement of the integrated-utility "death spiral" 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 (Costello & Hemphill, 2014; Felder & Athawale, 2014; Khalilpour & Vassallo, 2015; Severance, 2011). Tariff are volumetric, i.e., depends on energy consumption (Faruqui & Hledik, 2015).

Renewable technologies pose a challenge in the power system, which is intermittency, as their output varies according to the available sunlight, wind speeds and wave activity. This creates flexibility and back-up requirements to balance any temporal inequality of the electricity system, current existing system is not able to offer these services (ramping up, ramping down, etc.) and the market rules are not yet adapted to value them (Cepeda & Finon, 2013). The variability and unpredictable nature of renewables poses a number of power system impacts, which can become challenging under high penetration levels of renewables (Brouwer et al., 2014).

2.3 Policy instruments to support renewable energies

Policies in favour of environmentally friendly technologies were designed to reduce green-house emission, and therefore threat of global warming. Different policies have been traditionally applied to encourage renewable energies reducing greenhouse gas emissions, some policies can lead to reduce directly greenhouse emissions while others can promote directly renewable energy (Haas et al., 2011). Renewables face entry barriers such as technical, economical and institutional (Timilsina et al., 2012). The technical and economic barriers may be overcome most easily if there is institutional clarity, for instance, regions with similar renewable resource, government support and regulatory initiatives may have significant differences regarding to renewable development. This is because of differences of institutional entrepreneurship, a supportive local institutional context is key for a successful implementation of renewable energies (Jolly, 2017).

Once institutional barriers are overcome, economic and technical barriers are also passed as consequence of virtuous cycles tied to learning curves and experience. An institutional context includes effective and appropriate policy instruments. These may facilitate the adoption of renewables making it more profitable (del Río, 2012; Romero & Rudnick, 2015).

The learning effects associated with increased market share of renewable technologies have led to potential cost reductions, making these technologies more attractive to investment (Lindman & Söderholm, 2012); subsidizing renewable energies breaks the vicious circle in which these technologies would remain expensive because they cannot be adopted and cannot be adopted because they are expensive (Del Río, 2009).

Some policy instruments to increase the percentage of renewable markets are feed-in tariffs, green certificates, renewable energy auctions and fiscal incentives. These instruments are also called Schemes of Support for Electricity from Renewable Sources or RES-E (Renewable Energy Sources Electricity) Support Schemes (Batlle, 2011; EC, 2008). Some of these instruments are defined below.

A fixed feed-in tariff is a payment granted to all renewable generators that inject their energy into the grid instead of the electricity price; a feed-in premium, is a fixed amount paid in addition to the wholesale electricity price (Rathmann, 2007; Schallenberg-Rodriguez & Haas, 2012; Leao et al., 2009). Most European countries and some states in Canada and the United States have opted for a fixed feed-in tariff, as only a few have opted for a feed-in premium, such as Spain, Denmark and the Netherlands. Likewise, in most countries the cost of the feed-in tariff is charged at the price of electricity, although it may also be financed by the government (Lehmann, 2013). Feed- in tariff is the most widely used policy instrument to promote renewables all over the world (Ren21, 2016).

Additionally, some of the policy instruments for achieving the direct reduction of carbon emissions may be the carbon market, the carbon tax, or emission standards (De Jonghe et al., 2009). An example of a carbon market is the EU ETS (European Union Emission Trading System), in which the polluting companies must support each ton of CO2 emitted to the atmosphere with a EUA (European Union Allowance). In a carbon market under equilibrium conditions the EUA price is equal to the marginal cost of reducing emissions; the EUA price is internalized to the price of electricity produced by fossil generators (Thema et al., 2013; Delarue & D'haeseleer, 2008). The carbon tax studied by Pigou is not linked to a market and consists of charging the emitters for the negative externality caused by contaminating (Chappin, 2011).

Other policy instruments can be implemented simultaneously with the carbon market or carbon tax, for example, a carbon market with floor at the carbon price. This is because the price of carbon may not be high enough to promote the investment of low carbon technologies due to barriers and market failures (Cowart, 2011). Most countries have several policies in place that covers the same emission source, for instance in the European Union following policy instruments are applied to reduce emission from the electricity sector: EU Emission Trading System (ETS), energy-efficiency standards and energy-efficiency labels on electric motors and appliances, carbon taxes, feed-in tariff, feed-in premium or renewable portfolio (Lecuyer & Quirion, 2013).

Renewable energies affect security of supply by reducing peak electricity prices which are signals of capacity investment for flexible marginal technologies (Cepeda & Finon, 2013). An optimal energy policy must guarantee security of supply, environmental quality and low electricity prices (Moreno & Martínez-Val, 2011).

Some authors have focused exclusively on the policy instruments use to support solar PV, which are basically the same used to support the rest of renewables. For instance, Timilsina et al., (2012) highlight following supportive policy instruments: feed-in-tariffs, investment tax credits, subsidies, favorable financing, mandatory access and purchase, renewable energy port- folio standards and public investment. Yamamoto (2012) indicates that the most used policy instruments to remunerate PV electricity produced by households are: feed-in tariff, net metering and net purchase and sale. With a feed-in tariff, electricity utilities have the obligation to buy all PV- generated electricity of households at a set price during a given number of years. But, households must also pay for the electricity consumed from the grid at electricity rates.

Under net metering, PV generation is used to offset electricity consumption at other times, a credit equivalent to the retail electric rate is received for each kWh produced (Satchwell et al., 2015b). If, by the end of a billing period the amount of PV generation exceeds the amount of electricity consumption, the PV owner is paid at a set price; otherwise, PV owner must pay the net amount at electricity rate (Yamamoto, 2012). With a net purchase and sale, the electricity production and consumption are compared constantly, not like net metering where comparison is at the end of every billing period, and the electricity utility purchases the surplus generation at a set price (Yamamoto, 2012).

Many argued that though policy instruments to encourage renewable energies bring benefits, also bring drawbacks if their application is uncontrolled, affecting affordability (Antonelli & Desideri, 2014). Therefore, these incentives should be reduce steadily -through digression factor- when there is technological progress that leads to reduction of generation costs (Del Río, 2012; Del Río & Mir-Artigues, 2012).

As renewable energy sources are reaching grid parity, some policymakers question the need of feed-in tariffs. Particularly, feed-in tariffs for solar PV have been cut during the last years in several countries such as: Italy, Spain, Greece, Romania and the Czech Republic; in Spain, cuts were made in 2008 passing from 2758MW to 60MW in 2009 (KPMG, 2015). Despite of the advent of grid parity, after the reduction of feed-in tariffs, investments in new solar capacity have decreased (as shown in **Figure 8Error! Reference source not found.**) (Karneyeva & Wüstenhagen, 2017).

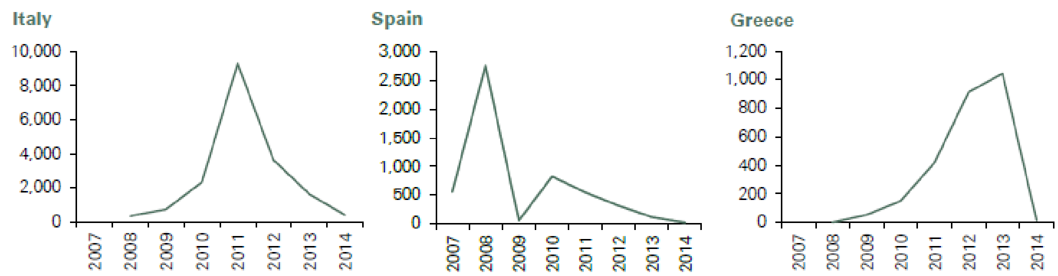

Figure 8. PV industry "cliff-edge" in Italy, Spain and Greece (Additional PV MW/year deployed).

Source: KPMG (2015).

2.4 Conclusions

The future for traditional utilities seems very uncertain. The falling electricity demand, rising tariffs, renewable energy growth and the empowerment of customers are the main challenges for utilities (Sioshansi, 2015).

Though some projections of economic growth are positive, the increase of electricity demand will be lower. From 2005 to 2012, world GDP rose by 3.7%/year while world electricity demand increased by 3.2%/year (IEA, 2016). The forecast of IEA (2016) for demand growth is 1.9%/year from 2012 to 2040 and GDP growth of 3.3%/year.

Furthermore, future electricity demand will be supplied mostly by renewable energy sources. Studies show that a number of countries (developed and developing) are promoting renewable technologies in their generation mix (REN21, 2016). As consequence, in the long-term fossil technologies will progressively lose market share.

Rooftop solar PV is each time cheaper facilitating customers to become independent. But this not the only innovation, also demand response technologies such as home energy management, storage, Electric

Vehicles, zero net energy buildings, smart devices/prices and micro grids are modifying the role of customers, empowering self-generating consumers (Sioshansi, 2015).

Analysts agree that power industry is on the brink of a massive transformation, some of the opinions about the future can be summarised as follows (Sioshansi, 2016): future will be decentralised, integrated, renewable, regulated and energy storage.

The energy storage development needs the grid for: equity purpose while lowest income individuals can adopt, as a back-up, for essential services (for example: hospitals or prisons) in densely populated cities where there is not enough space for solar PV panels, for injecting energy excess from PV systems (J. Green & Newman, 2017). Furthermore, the integration of distributed energy resources to the grid requires significant investments in distribution and transmission networks and grid modernization.

Though a diverse supply mix is needed to ensure flexibility and reliability of security of supply. Investments in new-large scale plants are not safe, at least if these are pollutive sources. It is not yet clear what actions should be taken. Investments will depend on the specific conditions of each country. A sustainable transition requires new legal framework and economic structure, focused on three goals: sustainability, security of energy supply and competitiveness.

Chapter 3. Measures to face transition

The age of renewable power is underway; the power sector will move toward a more decentralized electricity system with renewable energies to the forefront, particularly, solar power from distributed PV. The trends driving change are favorable regulatory for PV deployment, as well as continuing decreases of PV costs and rising electricity tariffs. These favorable conditions have led to dramatic growth of solar PV for several countries around the world (REN21, 2016), currently, the expectations of solar PV growth are high as its attractiveness keeps improving. This issue poses challenges for utilities such as under-cost recovery of fixed cost, cross subsidies and technical problems (Bayod-Rújula, 2009; Eid et al., 2014; Ruester et al., 2014). Additionally, in the worst scenario of successful PV market penetration, utilities could face a "death spiral", where customers reduce their energy consumption using solar PV generation, and utilities increase rates to cover fixed costs, this provokes further PV adoption and rate increases. For some death spiral seems unlikely − since it entails a regulatory inaction and myopic behavior of utilities −, but, it is undeniable the impact on revenue as energy usage declines due to solar PV generation.

In fact, different scholars argue that rooftop solar PV erodes revenue of utility: Satchwell et al. (2015a), Eid et al. (2014) and Oliva et al. (2016). Though, in some places distributed solar PV is yet too low for causing significant impacts of revenue for utilities, many utilities and regulators are seeking to avoid more-acute problems in the future. Basically, reforms to tariff structures, changes to compensation schemes and new business models are proposed to mitigate distributed solar PV impacts (Darghouth et al., 2016). **Table 1** summarizes the possible strategies applied to avoid possible consequences of distributed solar PV such as: increased retail electricity rates and cost-shifting to non-solar customers, reduced utility shareholder profitability, and reduced utility earnings opportunities (Barbose et al., 2016).

Table 1. Strategies to Address Concerns about the Utility Financial Impacts of distributed solar PV

Strategies	Stakeholder concerns addressed		
	Increased retail rated and cost-shifting	**Reduced utility shareholder return on equity**	**Reduced utility earnings opportunities**
Reduce compensation to DPV customers	✓	✓	✓
Facilitate higher-value DPV deployment	✓	✓	
Broaden customer access to solar	✓		
Align utility profits and earnings with DPV		✓	✓

Source: Barbose et al., (2016)

The rapid growth of distributed solar PV in USA is due to the combination of net metering and volumetric retail pricing (SEIA, 2013). Net metering allows PV customers to remunerate each solar PV kWh at a retail electricity price, promoting high levels of distributed solar PV in states with high retail electricity prices and/or solar radiation (Barbose et al., 2016). Volumetric retail pricing means that rates are roughly calculated as the fixed network cost divided by the energy consumption, when energy consumption is reduced rates increase to maintain the covering of network costs (European Commission, 2015). Many argue that this kind of charge is not cost-reflective, advocating for demand charge that depends on the peak demand of each customer (Hledik, 2014).

Modifications on net metering and rate design are based on following concerns (Barbose et al., 2016):

- Increased retail rates and cost-shifting: solar PV generation reduces energy sales, this results in a loss of revenues. This also reduces utility cost for savings though cost saving is lower than revenue reductions. Consequently, utilities will increase rates to recover their costs, additionally PV customers will be charged, with lower energy than non-PV owners though both are using the network as a back-up.

- Lower utility shareholder return on equity (ROE): as rates are mainly volumetric, i.e., depends on the volume of sales, reductions from PV self-generation also reduces revenue collection and consequently the utility shareholder ROE. **Figure 9** represents a comparison between monthly required revenue and monthly actual revenue, the unforeseen adoption of distributed solar generation leads to an actual revenue lower than the required revenue for utilities (grey area represents the losses).

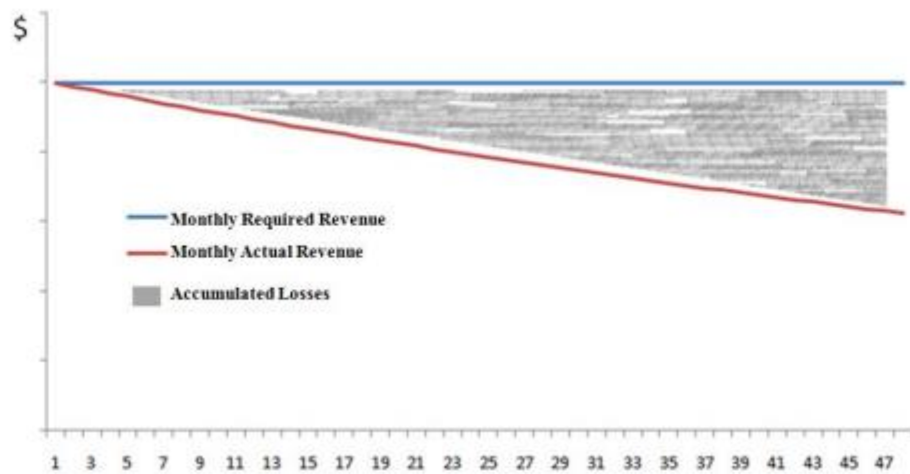

Figure 9. Required revenue vs actual revenue under unforeseen high PV adoption.

Source: Gianelloni et al., (2017)

- Inefficient allocation of resources: Net metering may lead to over-or under incentivized to install distributed solar PV, for example solar PV adoption may occur in not the most valuable manner in terms of location, size and orientation. This is important to achieve policy goals such as grid modernization or reduction of greenhouse gas emissions.

3.1 Rate Design Reforms

There are concerns about poor alignment between the traditional utility business model − which is capital intensive and highly dependent on energy sales – and recent advances in distributed generation that carry to reduction of energy sales and opportunities for capital investments (Kind, 2013).

Distribution business is considered a natural monopoly; thus, regulators intervene to avoid any monopolistic behavior. Regulatory objective of maximizing social benefit, while maintaining the economic-financial balance of network operators, requires matching total revenues and total costs used for the service. The regulatory problem lies in determining the efficient level of providing the service (Mercados energeticos consultores, 2014).

In practice, regulators apply various regulatory mechanisms to determine the remuneration of distribution companies, such as (Joskow, 2008): Rate-of-return regulation, Incentive-based regulation and Yardstick regulation. These three approaches are described next (Picciariello, 2015): Under rate-of return regulation, distribution companies report their operation costs to regulators, who use them to define a reasonable profit (rate of return) for the distribution company. Incentive-based regulation sets caps to electricity prices, these caps are defined considering a productivity factor X, that provides a high incentive for a network company to achieve a higher productivity to gain more profits. Finally, yardstick regulation is a way of benchmarking where each company is rewarded based on its performance compared to similar companies, the average costs of the group of similar companies are determined, being that the profits of each company will result from the difference between the revenues according to the tariff resulting from the average costs and the actual costs. As these regulatory schemes are beyond the scope of this thesis, this topic is not examined in depth.

Returning to the issue of reforms to tariff structures, frequently such reforms imply to reallocate a portion of the volumetric charge to fixed customer charges and/or demand charges (Faruqui & Hledik, 2015). Next, basic concepts about network tariffs are presented, such as types of network tariffs, rate designs for residential sector, tariff principles and charges to distributed generators.

3.1.1 Basic concepts about network tariffs

Use of System (UoS) Charge, also known as **distribution tariff** is paid periodically by network users to cover the recurrent operating and capital costs associated to the network investment and operation (Sakhrani & Parsons, 2010). **Both, use of system charges and connection charges must recover the allowed revenue of the distribution company**.

3.1.1.1 Types of network charges

The components of electricity network tariffs are (Firestone et al., 2006; European Commission, 2015; ActewAGL, 2015):

Fixed charge ($/customer/day or month): covers the cost incurred to provide the network service regardless customer's consumption, it is also known as standing charge or service charge and is charged to customers by connection point or residential consumer. Also, it is related to connection services.

Volumetric charge ($/kWh)**:** also called energy usage charge, it is levied on each unit of energy consumed. Further, it covers the variable network costs related to the cost of constructing, maintaining and servicing distribution assets.

Capacity charge ($/kW): also known as demand charge, it is applied on the consumers' maximum demand used during a specific time range; it remunerates the fixed cost linked to the infrastructure for supplying peak demand in proportion to the capacity required by each customer, it should be an incentive for consumers to manage their load.

Other components are reactive energy ($/ KVArh) and loss energy (European Commission, 2015). Volumetric charges and capacity charges can have different structure according to the way they are metered i.e. both can be flat, variable or Time of Use TOU. A flat charge is a fixed charge for a fixed amount of energy or pre-defined capacity; a variable charge matches different rates for each level of capacity or consumption; finally, in a TOU charge the rate depends on different times of consumption (Firestone et al., 2006; Eurelectric, 2013; Picciariello, Reneses, Frias, & Söder, 2015). Thus, residential tariffs can be categorised depending on the amount of customer's usage or consumption and the time of consumption. **Table 2.** provides information about the tariff components applied to household consumer across EU Member States.

Table 2. Distribution tariff component identified by country for residential sector

Country	Fixed charge	Capacity charge	Energy Charge (volumetric)
Autria	Yes, depending on anual consume	Yes, depending on anual consume	Yes
Croatia	Yes	No	Yes

Czech Republic	Yes	No	Yes
Denmark	No	No	Yes
Estonia	No	No	Yes
Finland	Yes, depending on DSO	No	Yes, depending on DSO
France	Yes	No	Yes
Germany	Yes	Yes	Yes
Hungary	Yes	No	Yes
Ireland	No	Yes	Yes
Italy	Yes	No	Yes
Lithuania	No	No	Yes
Luxembourg	No	No	Yes
Poland	No	Yes	Yes
Portugal	Yes	No	Yes
Slovakia	Yes	No	Yes
Slovenia	Yes	No	Yes
Spain	Yes	No	Yes
Sweden	Yes	No	Yes
Netherlands	Yes	Yes	No
Great Britain	No	Yes	Yes

Source: European Commission (2015)

3.1.1.2 Tariff principles

Proper tariff design must follow economic or regulatory principles, which are based on system sustainability, economic efficiency and consumer protection (Sakhrani & Parsons, 2010; Rodríguez Ortega et al., 2008; Pérez-Arriaga et al., 2013; Picciariello et al., 2015).

System sustainability principles:

- Universal access, all consumers must have access to electricity;
- Complete cost recovery through tariffs of the allowed costs;
- Additivity of components, final tariff must be the sum of different tariff components that remunerate each activity relate to the electricity supply chain (generation, transmission, distribution and commercialization).

Economic efficiency principles:

- Productive efficiency, network services must be delivered to consumers at the least cost possible;
- Allocative efficiency, network tariffs must reflect how much customer value the network service provided. Thus, tariffs would allow to send economic signals that stimulate efficient operation and investment;
- Cost-causality or cost reflectiveness, network tariffs should reflect the contribution of each network-user to the network costs;
- Equity or non-discriminatory, network-users that belong to the same customer group should be charged the same, regardless of the end-use of electricity or customer's characteristics.

Consumer protection principles:

- Transparency, the adopted methodology for computing must be available to the public;
- Simplicity, the tariff methodology must be easy to understand and implement;
- Stability, for reducing uncertainty of investment decisions tariffs should be stable in the short-term and gradually change in the long-term.

A regulator must decide which principles to prioritize as some of these principles may present conflicts between them; for averting death spiral the key pricing principles could be cost reflectiveness and system sustainability principles. To avoid death spiral rate design may be the right measure, because the transmission and distribution of fixed costs is recovered via volumetric charges, cost recovery is threatened when volume of sales decreases, further over-recovery of costs may occur if volume of sales increase (Felder & Athawale, 2014).

3.1.1.5 Arguments to reform rate structures

Following arguments are used in favour of modifying rate structures, for example: to introduce a demand charge, increasing fixed monthly charge, a time-of-use etc (Faruqui & Hledik, 2015):

- Introduce a demand charge ($/kW) for customers with DG, a demand charge is charged to consumers based on maximum demand (kW) of consumer over a time period (usually a month). Because of most capital grid investments are driven by maximum demand of the system, a demand charge may be more suitable to align customer payments with the cost they imposed on the system.
- Raise the fixed monthly charge. A fixed monthly payment is proportional to fixed customer costs and comes with an energy charge, fixed monthly payment is not related to generation, transmission or distribution. Therefore, increasing fixed charge would allow utility to recover a portion of capital investment.
- Include time-of-use tariffs. With time-differentiated prices, higher prices are charged during on-peak hours and lower prices during off-peak hours, this reflects the underlying cost structure, i.e., the corresponding variation of capacity and energy costs during on-peak and off-peak periods.
- Include inclining block rate (IBR) structure: this proposal means a “flattening” of tariff, by reducing the prices in the upper tiers and increasing the prices in the lower tiers to diminish the price differential between tiers.

3.2 Reduced compensation to distributed solar PV

Under net-metering DG owners receive retail electricity price (equivalent to the sum of energy cost, transmission and distribution charges), as the reimbursement to DG customers is greater than utility cost savings, to protect themselves from revenue erosion utilities will increase rates (A. Brown & Lund, 2013). In the end, the utility will not lose during this transition because the increase of rates is paid by non-DG customers (frequently the less affluent customers) creating a gross inequity between customers (Faruqui & Hledik, 2015). Some regulators recognize that is not economically feasible an unlimited net-metering, indeed, politicians have proposed several measures to reform net-metering. With these proposals DG customers pay for the electricity consumed from the grid at the full retail rate, but separately are compensated for the energy exported to the grid at a price that reflects better the value of electricity (Faruqui & Hledik, 2015). These proposals are described next:

Net billing: 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 & Bernal-Agustín, 2015).

Feed-in tariff: each kWh of electricity produced by solar PV systems generate, the owner is paid at a rate greater than the retail price, according to the type of meter recording an owner may receive the incentive for all the electricity generated by their panels or only the surplus fed into the grid (Zahedi, 2010).

Value of solar tariff (VOST): this payment should capture the net value of distributed PV for the electricity network to avoid overpayment by non-solar customers, VOST considers independently energy consumption from generation, for example: DG customers buy the energy consumed from the grid at retail tariff and sells all the energy produced at prices that reflect the utility's avoided cost (related to generation) (Costello, 2015).

3.3 New business models

The research adopts the definition of business model proposed by Osterwalder & Pigneur (2009): "the rationale of how an organization creates, delivers and captures value". Osterwalder & Pigneur (2009) suggest using the business model canvas, which has four basic pillars: the value proposition, the customer interface, the infrastructure management and the financial aspects.

The focus of this section is to highlight some new and innovative emerging business models, as the role of traditional "utility" becomes threatened by energy trend of decentralisation, it is urgent to identify new business models. According to Abella (2015) new business models can be categorised in three main pillars, as shown in **Table 3**.

Table 3. New business models

Distributed Power Generation business models	***Demand management business models***	***Business models in regional aggregation systems***
• Supply of Distributed Generation Systems • Leasing • PPA (Power Purchase Agreement) • Rent the space model	• ESCOS • Supply of smart home solutions • Demand response	• Community solar • Microgrid • Virtual power plant

Source: own elaboration from Abella (2015)

3.3.1 Distributed power generation model

This type of business model promotes "prosumers", i.e., the consumption of electricity and energy production fed into the grid. Within this category, it is possible to identify three branches: supply of distributed generation systems, leasing services or power purchase agreements, and the rent-the-space model. Which are described next.

3.3.1.1 Supply of Distributed Generation Systems

This is the simplest business model, the sale of power generation systems and accessories. **Figure *10*** shows the different types of business models dedicated to this activity, which can be categorised as: design, installation, maintenance and operations.

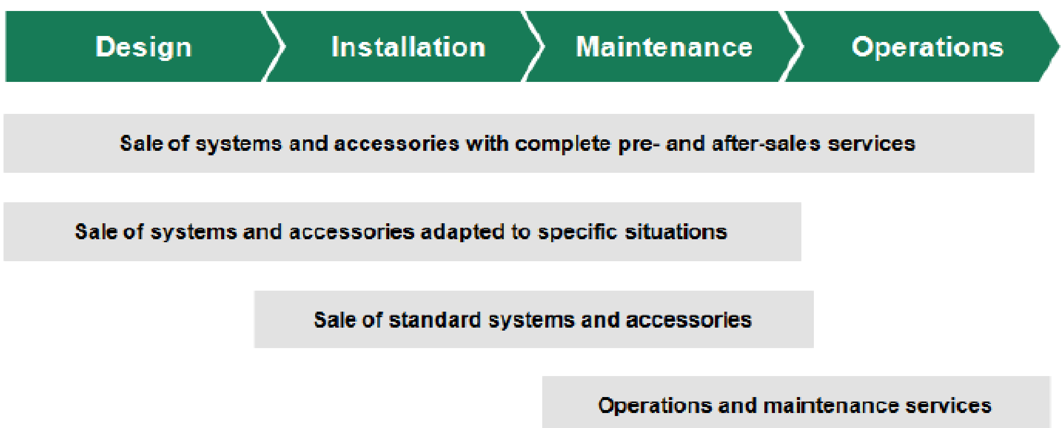

Figure 10. Value Chain for the Supply of Distributed Generation Systems Business Sub-models

Source: Abella (2015)

3.3.1.2 Leasing service

In the leasing business model, a fixed monthly payment is made to the solar company by customers; for this a contract of 20 years is signed between customer and company, at the end of the contract: renewal, to sign other contract or free removal. The key success factors are: (i) Net savings greater than lease free; (ii) the leasing company must be financially strong (Zhang, 2016; Tongsopit et al., 2016).

3.3.1.3 Power purchase agreement (PPA) service

In the PPA business model, a fixed monthly payment ($/kWh) is made to the solar company by customers; for this a contract of 20 years is signed between customer and company, at the end of the contract: renewal, to sign other contract or purchase the system. The key success factors are: tariff PPA lower than grid tariff (Zhang, 2016; Tongsopit et al., 2016). Solar city is an example of a leasing/PPA company.

3.3.1.4 Rent the space model

Under this business model, there is a contract with a duration of 20-25 years between the company and the rooftop's owner. Here, electricity retailer can be developer, when contract ends customers can buy the system. The key success factors are: developer should receive a feed-in tariff, roof rental fee must be attractive for rooftop's owner, who must also be reliable (Zhang, 2016; Tongsopit et al., 2016). An example of this type of company is: Green Nation in UK and Toshiba International Europe in Germany.

3.3.2 Demand management business models

3.3.2.1 ESCO

An ESCO is a company that provides its customers with energy services, related to energy conservation services (the act of saving energy by reducing a service) or energy efficiency (saving energy keeping the same level of service) (Larsen et al., 2012). These services are provided through long-term contracts with a duration between 5 and 25 years, an ESCO is categorized in two types of business models: (i) Energy supply contracts (ESC) that provide useful energy such as hot water, coolant, electricity etc.) (ii) Energy performance contract (EPC) is used to provide final energy service such as space light, space heating etc (Bolton & Hannon, 2016; Hamwi & Lizarralde, 2017). Examples of these kind of companies in the world are: Johnson Control Power utilities: ConEdison, Direct Energy, Pepcp, Constellation Energy In UK and Germany: Centrica, EON, EnBW, Vattenfall, RWE (Abella, 2015).

3.3.2.2 Smart home solutions

It requires the implementation of smart meters, these smart home solutions can be divided into three business sub-models (Abella, 2015)**:**

- Sale of smart home systems, two types of systems:

-Control systems for sources of consumption: allow end users to monitor household and/or sub-system power consumption by remotely controlling different sources of consumption such as heating/cooling, lighting, electrical appliances. Verify that all household devices and lights are turned off. In the afternoon, one hour before returning home

-Automated systems to control and manage sources of consumption: The same but automatic, self-regulate according to consumer habits and external factors, such as weather conditions

- Household consumption recommendation from retailers**:** Developing a collaborative relationship between individuals and power retailers, retailers offer their customers personalized recommendations to optimize household power consumption. Recommendations usually increase consumer awareness regarding the benefits of shifting part of their consumption to non-peak price hours
- Recommendations from new companies: similar to earlier business model but recommendations are offered by non-utilities companies.

3.3.2.3 Demand response aggregators

Power supplies may not be enough to meet demand. Because fluctuations in generation levels from renewable sources or demand spikes. When faced with imbalances, demand response aggregators can temporarily reduce demand in order to re-establish power supply-demand balances (Behrangrad, 2015). The utilities which can offer demand response programs such as GDF Suez Energy, and nPower in collaboration with Flexitricity For instance: Enernoc which operates in the US, Australia, Canada, Germany, Ireland, Japan, New Zealand and UK (Abella, 2015). **Figure 11** shows how DER technologies may be used to provide downward and upward adjustments to the grid.

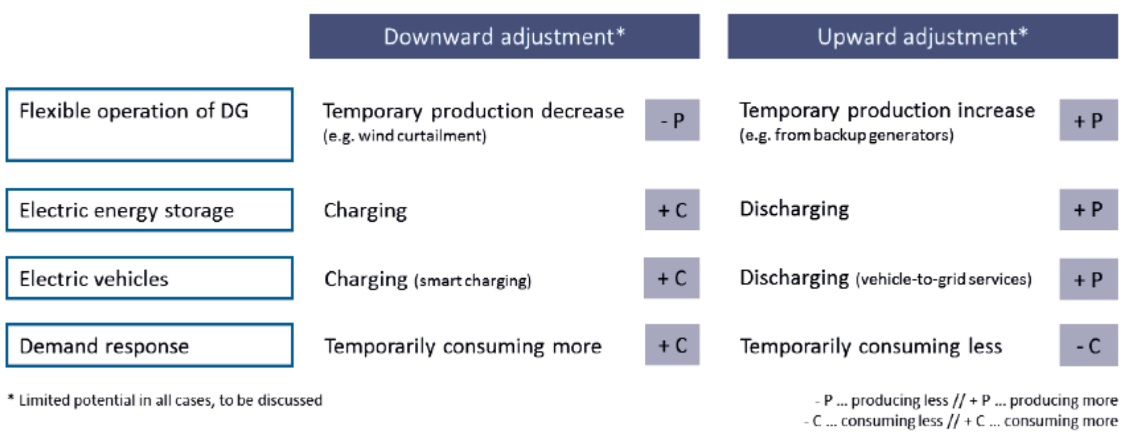

Figure 11. DER'ability to provide downward and/or upward adjustment to the system

Source: Pérez-Arriaga et al., (2013)

3.3.3 *Regional aggregation business models*

3.3.3.1 Virtual Power Plants (VPP)

VPP and microgrid represent the integrated systems category within smart energy unlike microgrids, virtual power plants can potentially be used to negotiate the sale of power on a wholesale market. VPP is a cluster of distributed generation units which is controlled by one entity and is capable of supplying energy via the power grid at specific times, as if it were a single generation plant. Use in the event of supply-demand imbalance (Helms et al., 2016).

3.3.3.2 Microgrid or energy communities

Microgrids are groupings of power generation sources and consumers which are interconnected at the local level, generation is handled by prosumers storage systems which allow microgrid being autonomous (Asmus, 2008). Power is used for themselves and public services, being isolated or connected via one connection point (to cover shortfall or inject surplus) (Noll et al., 2014). Some argue that solar communities may alleviate revenue losses related to the penetration of distributed solar PV (Funkhouser et al., 2015), indeed the utility may have a higher control on this penetration with this type of business model (Barbose et al., 2016).

3.4 Other reforms

Other measures may be adopted to face transition toward a decentralised and cleaner power system, and particularly to face the penetration of distributed generation. These alternative measures are: connection charges and market decoupling, which are described below.

3.4.1 Connection charges

Network tariffs can be classified according to different services such as connection charge or use of the network system. Connection charges are paid just once by DG owners for covering the non-recurrent cost of connecting to the network and receive network services; they are categorised as deep, shallow and shallowish (Sakhrani & Parsons, 2010). These network charges for distributed generation are very important to get proper investment signals for DG, these charges should be paid by DG operators. In a deep charge, a DG producer bear the reinforcement cost –cost related to necessary new network investments for integrating DG into network, include the direct costs of grid accession–; in a shallow charge the direct cost of the connection is bear for DG producer but not the reinforcement cost, which is paid through the use of system charges by grid users; finally, in a shallowish charge, the DG producer bear the direct cost of the connection and a share of the reinforcement cost while the other share is paid by distributor system operator (Frías et al., 2009).

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 subsidization 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 connection charge 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; López & Steininger, 2015). Connection charge 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 (López & Steininger, 2015).

There are other measures that point to the same direction of connection charge. According to Faruqui & Hledik (2015) these measures are: Firsts, a DG output which entails to charge DG customers based on the total amount of electricity that they produce from on-site generation each month, this fee reflects the customer’s cost of using the distribution system. Second, a capacity charge to DG customers based on their installed capacity of their solar PV systems, the arguments behind this proposal is that customers with larger PV systems avoid paying a larger portion of grid costs because they self-generate more electricity. Third, imposing a minimum bill, this means that all customers will pay a minimum fixed amount each month, the argument is that a minimum bill amount can be associated with the average customer’s cost of using the grid.

3.4.2 Revenue decoupling

Historically, fears to revenue erosion of utilities may be associated to energy efficiency programs, which also reduce the energy consumption from the grid. Different ratemaking practices have emerged as a strategy to face consequences of energy efficiency. For example, revenue decoupling and lost-revenue adjustment mechanisms (LRAMs) reduce the lag between retail electricity prices and the moment they are applied, which alleviate the effect of PV penetration on utilities (Barbose et al., 2016). In general, these measures seek to ensure to utilities constant revenues and profits regardless of how much energy they deliver (Brennan, 2013). For instance, if there is revenue losses during this period, it will be offset next period with an increase of the tariff; in the opposite case, if there is revenue surplus this year, it will be offset next period with a reduction of the tariff (Nissen & Williams, 2016) (See **Figure 12**). However, this measure may foster customers to adopt behavior of energy conservation (save energy) (Abrardi & Cambini, 2015). In the case of distributed solar generation, this is a short-term solution for a long-term problem.

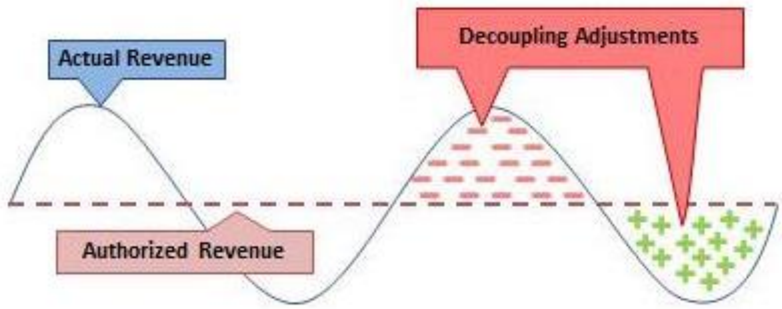

Figure 12. Decoupling adjusts rates.

Source: connect.xcelenergy.com (2017)

3.5 Strategies from utilities

Utilities can adopt different strategic stances regarding to this imminent change provoke by renewables. Potential responses for utilities are to "Fight", "Flight" or "Innovate", which are not necessarily mutually exclusive reactions (Green & Newman, 2017). When utilities chose "Fight" they will resist to changes and promote protectionist policies, "Flight" means utilities will not assume any action, and "Innovate" implies seek new business models.

The utility companies that decide to fight are choosing a *defensive* strategy while those who decide to innovate are choosing a *proactive* strategy (Stenzel & Frenzel, 2008; Huijben et al., 2015).

With a *defensive strategy*, different measures to ensure fully cost recovery would be encouraged for utilities to maintain the status quo. A measure could be to change the tariff design to reflect the costs imposed by each network user, e.g., to add a fixed charge or demand charge to volumetric rate (Faruqui & Hledik, 2015). Likewise, as the government compensation scheme enables PV adopters to pay lower energy bills than non PV adopters, utilities could advocate for reducing the compensation received by PV adopters for power generation based on fairness arguments to avoid free-riding (Darghouth et al., 2016). While an important question about the value of solar energy arises, a similar argument is used to increase the PV cost using connection charges. Although, these measures are antithetical to renewable energy efforts because they halt solar PV development, they have been already implemented in some countries (Faruqui & Hledik, 2015).

Instead of opposing solar PV adoption, a *proactive strategy* offers a long-term solution to the problem. It requires a move towards new business models, exploiting current capabilities and developing new ones, where the crux is to evolve quickly enough to adapt to environmental change. Richter (2013) argues that utilities in industrialized countries may be have reluctant to innovate with new business models because of conflict with current business models and risk aversion. However Richter (2013b) shows that business models for solar PV are the keystone to manage the transformation of the power industry toward renewable energy sources.

Utilities could therefore must rethink their business models − how an organization creates, delivers and captures value (Osterwalder & Pigneur, 2009) − and to convert the solar PV threat into an opportunity. A system thinking approach of the dynamics of PV business models could help to utilities to make decisions about their future. Existing literature provides useful information about: (i) the effect of distributed solar generation on power industry (e.g., Costello & Hemphill, 2014; Ford, 1997; Cai et al., 2013; Darghouth et al., 2016; Grace, 2015; Eid et al., 2014); and (ii) Photovoltaic new business models for utilities (e.g., Frantzis et al., 2008; Sauter & Watson, 2007; Huijben & Verbong, 2013; Overholm, 2015; Zhang, 2016; Tongsopit et al., 2016; Drury et al., 2012; Strupeit & Palm, 2015).

Utilities will invest on new business models according to their capabilities. If a utility has stronger capabilities in conventional technologies, this will prefer to invest in these technologies instead of renewable technologies, the reluctance to invest in renewable technologies is called strategic rigidness (Nisar et al., 2013). For instance, even utilities as Iberdrola the world's largest wind energy developer can present strategic rigidness. At the beginning Iberdrola is strong in hydroelectricity, nuclear and renewable generation technologies, nowadays Iberdrola is positioned as a green company (Shah et al., 2013; Poisson-de Haro & Bitektine, 2014). However Nisar et al (2013) indicated that “Iberdrola’s core competences in wind energy has made it strategically rigid in terms of adopting an innovative technology, i.e., concentrated solar power” (Nisar et al., 2013).

On one hand, utilities with strong capabilities in conventional technologies may survive to disruptive technologies such as renewable distributed generation. That is demonstrated by Endesa, which used the support of the Spanish government to maintain its energy mix (composed by coal, hydro, nuclear, oil and gas) due to its role in the electricity market as guarantor of the security of supply. On the other hand, Union Fenosa has a high coal energy participation and low support from Spanish government (Poisson-de Haro & Bitektine, 2014).

As electric utilities may face increasing pressure from climate change which leads them to transform their energy portfolio; electric utilities have preferred large-scale over small-scale renewable energy projects due to risk return expectations and transactions costs (Richter, 2012), however cost reduction of distributed generation technologies may motivate the opposite. Distributed generation must not be underestimated for electric utilities, on the contrary electric utilities must consider it as a new disruptive technology that may change the market structure. It is not completely clear how these companies must venture in this new business model for creating value, nevertheless if electric utilities do not act quickly an important market share may be lost until competitors, electric utilities must achieve the exploitation of current capabilities and simultaneously explore new capabilities to survive and succeed (Richter, 2013b).

3.6 Conclusions

The development of DG poses opportunities, yet also challenges for electricity market agents. The opportunities could be to provide ancillary services and develop new business models; while the challenges are related to volatility of net demand or local over-voltage (Lopes et al., 2007; EPRI, 2014). Particularly, DG when based on solar photovoltaic PV, may be inconvenient to traditional business models of utilities, as costs have been showing swift reductions in recent years (Costello & Hemphill, 2014; Bronski et al., 2014); and these have also pressed further losses to utilities in terms of customers, sales and profits (EPRI, 2014; Satchwell et al., 2015a). This problem could be exacerbated, as utilities increase tariffs to recover network costs encouraging PV adoption and further tariff increases − producing a vicious circle also known as utility death spiral (Castaneda et al., 2017a).

Around the world, government and utilities have implemented measures to face the reduced electricity use due to increasing uptake of distributed generation. For example: Implementation of TOU tariffs, higher demand charges, higher fixed daily charges, low payments for PV export and imposition of network limits on distributed generation (Passey et al., 2013). Changes of rate design and compensation schemes are based on: cross-subsidies and revenue erosion of utilities. Any change should be founded on the right understanding of the costs and benefits of distributed PV.

Utilities can assume different stance to face the challenges posed by the increase in solar PV deployment, choosing a *defensive* or *proactive* strategy (Stenzel & Frenzel, 2008; Huijben et al., 2015).

With a *defensive strategy*, different measures to ensure full cost recovery would be encouraged for utilities, for example: to change the tariff design to reflect the costs imposed by each network user, to reduce the compensation received by PV adopters for power generation on the basis of fairness and avoiding free-riding behaviours (Faruqui & Hledik, 2015; Darghouth et al., 2016). Some of these measures have been already implemented in Spain and some USA states (López & Steininger, 2015; Faruqui & Hledik, 2015).

A *proactive strategy* offers a long-term solution to the problem. It requires a move towards new business models, exploiting current capabilities and developing new ones. Here, the crux is to evolve quickly enough to adapt to environmental change (Richter, 2013; Richter, 2013b).

While opportunities for new business models in industrialized countries come from climate change and energy efficiency improvements. In developing countries the opportunities to create new business models come from unfulfilled basic needs and micro-finance (Engelken et al., 2016).

Regarding the new business models that could be created, there is wider range of possibilities. Among these, it is necessary to highlight the solar communities. Utilities are motivated to develop solar communities to satisfy consumer demand and alleviate revenue losses related to residential solar PV, besides this business mode may exhibit lower operation costs than traditional third-party ownership model (Funkhouser et al., 2015).

Following chapter reviews the performed studies of this thesis on the topic of renewable energy effects on power markets and explains the improvements which have been suggested by this thesis in the field of simulating the effects of renewables on the power market.

Chapter 4. Identifying research gap from literature review

Though much has been written about the likely impacts of renewable energies on electricity markets (Cepeda & Finon, 2013; Cludius & Hermann, 2013; Jónsson et al., 2010; Sáenz de Miera et al., 2008), 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. This research studies the potential impact of renewable energy sources (RES) on electricity systems, specifically on the generation and distribution businesses, in the case of Colombia.

A broad spectrum of literature – based on the use of classical market models (Dillig et al., 2016; Wiebe & Lutz, 2016) – reports on the extent of the impact of large-scale penetration of renewables on power markets, particularly on integrated utilities. For instance, Ballester & Furió (2015) statistically test the effect of RES on wholesale markets; Brouwer et al., (2014), 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., (2008) use an agent-based approach for the German case. This overview shows that many authors have studied the effects of renewable energy sources over the energy market. Additionally, the impact of renewable penetration on power markets have been extensively studied as a result of policy incentives as shown in **Table 4**.

Table 4. Literature review environmental policies applied to power sector

Reference	Description	Methodology
Del Río (2010)	Analyses the interactions between energy efficiency measures and renewable energy promotion (ETS, TGC)	Qualitative method in a partial equilibrium framework
Skytte (2006)	Studies difficulties in these simultaneous goals: renewable energy deployment, emission reduction and minimising consumer prices (ETS, TGC)	Qualitative method in a partial equilibrium framework
Sáenz de Miera, del Río González, & Vizcaíno (2008)	Analyse the reduction of the wholesale electricity price as a	Regression analysis

	result of renewable generation, with the application of a FIT	
Hindsberger, Nybroe, Ravn, & Schmidt (2003)	Analyse for an international context the effect of tradable emission permits (TEPs) and tradable green certificates (TGCs) to the electricity sector	Partial equilibrium model
Linares, Javier Santos, Ventosa, & Lapiedra (2008)	Present a generation expansion model for the electricity sector; it considers the oligopolistic behaviour of firms, and ETS and TGC policies.	Market equilibrium model Linear Complementarity Problem (LCP)
Unger & Ahlgren (2005)	Study the effects of TGC and ETS in Nordic system	Partial equilibrium model Markal model
Nelson (2008)	Analyses the interaction between ETS y TGC in UK power sector	Partial equilibrium model
Palmer, Paul, Woerman, & Steinberg (2011)	Study three policies for United States which are: a cap-and-trade ETS, RPS for electricity production, and tax credits for renewable generators	Haiku model- deterministic simulation model
Rathmann (2007)	Assess the interaction of three policies ETS, FIT, and TGC over the power sector	Quantitative analysis
Böhringer, Löschel, Moslener, & Rutherford (2009)	Study the European Union ETS-RES E with a multi-regional y multi-sectorial model	Partial equilibrium model
Eid, Reneses, Frías, & Hakvoort, (2014)	Present the tariff reduction effect of solar PV distributed generation deployment, as	Quantitative analysis

	cross-subsidies, and cost recovery.	

Particularly, many authors have researched the financial effect of the penetration of PV-based DG on different stakeholders of the markets (Eid et al., 2014; Oliva H. et al., 2016; Satchwell et al., 2015b; Brouwer et al., 2014; Minnaar, 2016) – these studies have not taken into account the long-term dynamics of the system. Although many others have incorporated feedback cycles (Cai et al., 2013; Darghouth et al., 2016; Franco et al., 2015; Zuluaga & Dyner, 2007) 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.

Others have researched cross-subsidies, cost recovery and different tariff designs. For instance, Eid et al. (2014) study 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; this study is focused on Spain. The main conclusion from the study is that net-metering with increasing rolling time-frames, together with a volumetric charge, have the stronger impact on DSO income-reduction while cross-subsidies increase. Also, Picciariello et al. (2015) 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 computational model for carrying out 12 simulations of U.S. networks; further, they also propose a tariff design based on the cost-causality principle.

Other researchers have investigated the financial impact of solar PV systems' expansion on different stakeholders. For example, Darghouth et al. (2011) have estimated the bill savings of different electricity tariff designs obtained by residential and commercial PV customers; similar studies have been carried out by Satchwell et al. (2015a) and Satchwell et al. (2015b) who analyse, respectively, the financial impact of solar PV on utility shareholders and ratepayers, and different measures for mitigating them. In addition, Oliva et al. (2016) undertook a study in Sydney about the short-term financial impacts of PV systems on PV adopters, retailers, distributors and all electricity customers when different compensation mechanisms are applied.

In addition, the impact of high penetrations of distributed PV systems has motivated numerous publications in recent years about the utility death spiral issue from a conceptual and modelling perspective, as described below.

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. Findings suggest that feedback reduces the time for PV capacity to reach 15% of demand by around four months and could increase net-metering costs by 5–10%. Also, 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 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; also, there is no evidence of a death spiral – not even when the positive feedback effect is isolated.

Grace (2015) develops a system dynamics model for exploring death spiral impacts on DG adoption and storage in Western Australia. Results show that the decrease of solar PV costs drives high solar PV adoption, causing a death spiral, along with benefits for society in terms of lower energy bills.

Costello & Hemphill (2014) present a quantitative analysis to identify the necessary economic and regulatory conditions for a death spiral; however, this paper suggests the death spiral phenomenon as possible but of low probability, as it supposes an inert attitude from utilities and regulators toward death spiral difficulties.

In Ford (1997), a system dynamics approach to a death spiral in the electric power industry is shown; specifically: the situation experienced after the oil embargo in 1973, when U.S. utilities faced financial challenges and asked the regulators to raise electricity rates to cover their increased operating and capital costs. Then, regulators were concern about the response of utilities' customers to higher rates, which could lead utilities into a downward spiral.

Laws et al. (2016) explore the effects of the residential PV and storage adoption on the retail price of electricity, taking into account the inherent feedback cycles through a System Dynamics (SD) model. Their findings suggested that net metering reduce grid defection and therefore death spiral, whilst pricing structures that reduce compensation for PV adopters encourage grid defection.

Castaneda et al. (2017a) develop a simulation model based on SD methodology to assess the effects of renewable penetration such as merit-order effect and death spiral on an electricity utility. They conclude that 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.

Muaafa et al., (2017) built an Agent Based Model (ABM) to investigate the extent to which rooftop solar installation can erode utility revenue by the so-called death spiral. They found that the scale of rooftop PV adoption will be smooth and have minimal effects on energy reduction and tariff increases. However, they also warn that other forms of disributed generation such as solar communities may represent a major threath.

Whether death spiral is actually true or not, following scholars have demonstrated that rooftop solar PV erodes revenue of utility: Satchwell et al. (2015a), Eid et al. (2014) and Oliva et al. (2016). To avoid in the future more-acute problems tied to distributed solar PV, utilities and regulators resort to measures such as: (i) tariff reforms (implementing time-of-use, higher fixed charges or demand charges), (ii) changes to PV compensation schemes and (iii) new business models (Darghouth et al., 2016).

As regards the latter, Castaneda et al., (2017b) use a SD model to assess how different measures may limit revenue erosion and tariff increase, these measures were: higher fixed charges, connection fee and net-billing. They conclude that these measures achieve social welfare as affordability and development of solar PV systems, however, the longer time framework requires further institutional developments as the broad penetration of distributed solar PV seems unavoidable.

Both measures (i) tariff reforms and (ii) changes to PV compensation are studied in Castaneda et al., (2017b) to limit revenue erosion and tariff increase related to PV diffusion. New business models to address utility financial impacts of distributed solar PV have been less studied. Though, Satchwell et al., (2015b) use a financial model to quantify the efficacy of different policies for mitigating the financial impacts of distributed solar PV on utilities, among these policies to change to a solar business model, the results suggest that the compensation of revenue erosion depends on the percentage of solar PV assets.

Most articles about new business models focus on making an overview of business models through a literature review or qualitative analysis (see e.g., Huijben & Verbong, 2013; Strupeit & Palm, 2015; Zhang, 2016; Tongsopit et al., 2016). Additionally, PV has reached grid parity in some countries, and in others is very close to reach it. In a post-grid parity scenario the subsidies will be reduce to zero leading to the slowing down of solar PV penetration (as already experience in some countries (Karneyeva & Wüstenhagen, 2017)) which may be beneficial for traditional utility business model.

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 thesis 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 thesis further studies the consequences of the technology transformation using economic and social as well as environmental indicators.

Lastly, of all available modelling alternatives, this research has considered a system modelling perspective as it facilitates high levels of aggregation, the understanding of dynamic feedback processes and other complexities such as delays and non-linearities. 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 (Dyner, 2000; Ford, 2002; John D. Sterman, 2000). These features are not always incorporated in classical market models that have no interest in transitional stages but rather focus on equilibrium phases (Dyner & Larsen, 2001). A few authors, such as Grace (Grace, 2015), Laws et al. (Laws et al., 2016) and others (Castaneda et al., 2017a; Castaneda et al., 2017b; Jiménez et al., 2016), 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.

This chapter enables to pose the following research objectives.

4.1 Objectives

The point of departure in this research is that renewable energies along with other technologies such as distributed energy resources are reshaping power industry. The utilities and regulator must take decision to adapt to this new environment. The power industry transition must emerge ensuring sustainability, thus a policy intervention is necessary. In response to this need, this research investigates the opportunities and threats of utilities, as well as possible strategies to address troubling issues tied to this transformation. Additionally, results of this research are useful to utilities, regulator and customers. Then, the objectives of this research are posed below.

General objective

Develop a framework for assessing electricity utilities strategies, under environmentally friendly policies.

Specific objectives

1. Identify threats and opportunities for electricity utilities under friendly environmental policies for large-scale renewable technologies and micro-generation projects.

2. Develop a simulation model where different strategies for electricity utilities can be assessed.

3. Assess different strategies of an electricity utility, for different scenarios of environmental policies.

A framework refers to a "platform", a concept coined by Dyner (2000). Where a framework is a modelling tool that enables analyst to focus on conceptualization, learning, understanding, policy feedback appraisal and evaluation of alternative options. A framework has following features: it is a generic, modular, adaptable and transportable structure, capable of supporting the process of system analysis for intervention in each particular system (Dyner, 2000). The general objective of this research is to develop a framework to identify utilities' strategies for facing the transition toward a cleaner power industry. To achieve this goal, four specific objectives were defined.

In the first specific objective, a simulation model is used to reach a global perspective of the utilities position. The importance of this objective lies in the need of utility leaders to take a proactive approach to deal with the growth of renewables.

In the second specific objective, a simulation model is developed to assess different strategies of utilities. To build a simulation model a rigorous modeling method is applied, a formal computer simulation of the dynamic complexity of the power industry is used to design more effective strategies for utilities.

In the third specific objective, changes in the business strategy are assessed. Utilities could turn threats into opportunities, for example by including plans to replace their own technology with more innovative, more valuable customer services offered at competitive prices.

Finally, in the fourth specific objective, a robust strategy is posed by testing different strategies and analyzing which lead to best market position for utilities, a robust strategy that can readily adapt to sudden change.

Part II. Simulation model

Chapter 5. Proposed simulation model

5.1 Selecting the right modelling tool

Models showed in the previous sections are mostly based on Hard modelling techniques, these techniques are not appropriate under current deregulated environment characterized by high uncertainty (Lee, Tabors, & Ball, 1990) (See **Table 5**). For that reason electricity utilities need a different toolkit of methods for planning and defining their strategy in the long-term (Dyner & Larsen, 2001). Some of these methods are simulation models, which are: "an alternative to equilibrium models when the problem under consideration is too complex to be addressed within a formal equilibrium framework" (Ventosa, Baíllo, Ramos, & Rivier, 2005).

In addition, there is an inception to the power market of renewable technologies and distributed energy resources (DG, electric vehicles and storage). This adds complexity to the planning and forecasting process of the power industry (Ibanez-lopez et al., 2017).

Table 5. Change with respect to uncertainty as utility companies are deregulated.

Planning input	Uncertainty in key planning input	
	Monopolistic market	Competitive market
Price	Low	Medium high
Information	Low	High
Demand	Medium	High
Consumer choice	Low	Medium high
Regulation	Low	High

Source: Dyner & Larsen (2001)

According to Ventosa et al., (2005) the electricity market modelling trends are: optimization models, equilibrium models and simulation models (See **Figure 13)**.

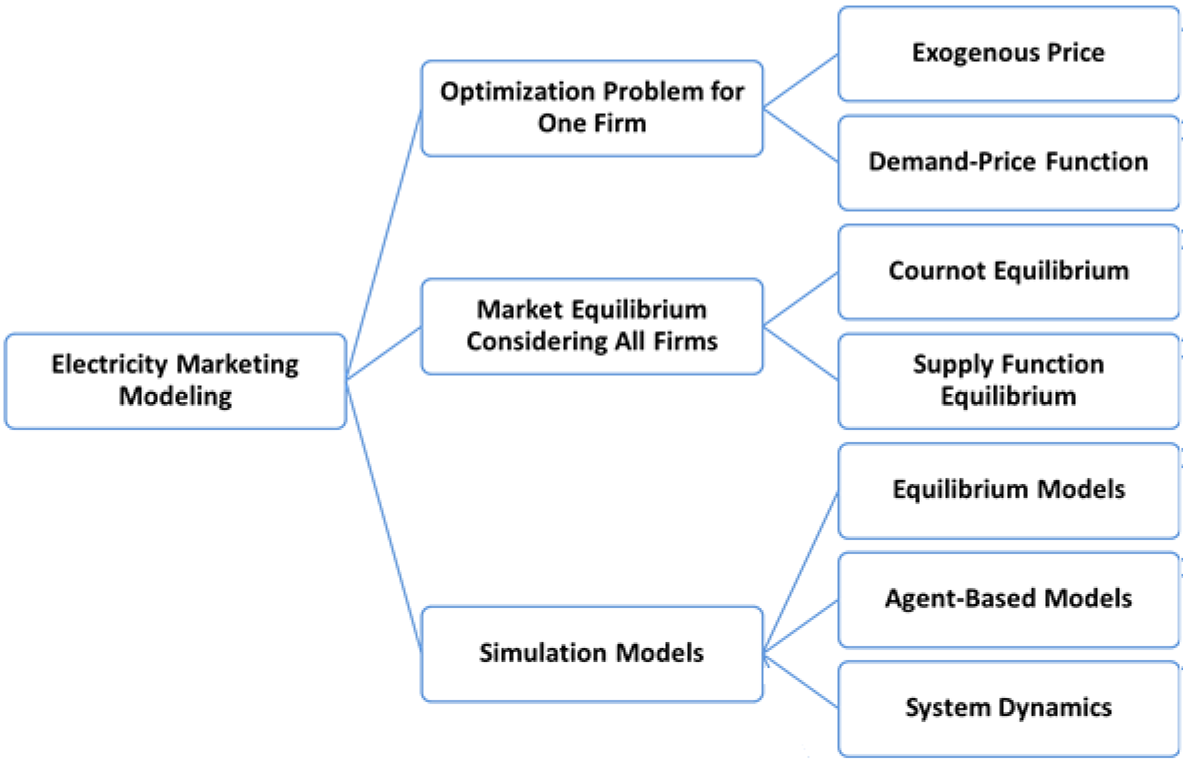

Figure 13. Schematic representation of the electricity market modelling trends.

Source: Ventosa et al., (2005); Bagdasaryan (2011); Borshchev & Filippov (2004).

Optimization models are for a single-firm, and there are two types: price modelled as an exogenous variable and price modelled as a function of the demand supplied by the firm. Both types can be deterministic or stochastic models. Traditional Linear Programming (LP) and Mixed Integer Linear Programming (MILP) techniques can be used to find the solution of optimization models.

Equilibrium models involve several firms, and there are two types: First, Cournot Equilibrium which uses algebraic equations, and second the Supply Function Equilibrium (SFE) which uses differential equations. In the Cournot Equilibrium model the main variables are quantities, not prices; this type of model focuses on the following topics: market power analysis, hydrothermal coordination, and influence of the transmission network and risk assessment. Finally, in SFE models "participants endowed with a cost curve find the equilibrium bid curve —i.e., a price-quantity offer— that maximizes profit"; this type of model focuses on topics such as: Market power analysis, representation of electricity pricing, linearization of the SFE model and evaluation of the impact of the electric power network (Ventosa et al., 2005; Kahn, 1998).

The following reasons support why optimization models are not suitable to treat the research problem posed in this thesis (Olsina, 2005):

- Market behaviour reflects the efficient allocation of resources, which is equivalent to a centrally-made optimization.
- Optimization models are prescriptive, i.e., they describe mainly the behaviour of the system under ideal conditions, which does not necessarily coincide with reality, representing what the market should be.
- Optimization models neglect feedback loops.
- Rate investments are set for permanently maintain an optimal trajectory.
- System evolves according to a of stable and optimal long-run equilibrium states.

Simulation models are more tractable than optimization and market equilibrium models. Some simulation models contain equilibrium models; which are used for making decisions. For instance: Otero-Novas et al., (2000) combine simulation and Cournot model, and Day & Bunn (2001) combine simulation and SFE scheme. Simulation models reproduce the actual observed market behavior no matter whether is ideal or not (Dyner & Larsen, 2001). Simulation models facilitate to capture soft elements present in real markets such as bounded rationality (theory that recognize that investors are not fully rational when making decisions), learning abilities, information asymmetries, etc (Ventosa et al., 2005).

A simulation model is defined as "a set of rules that define how the system being modelled will change in the future, given its present state" (Borshchev & Filippov, 2004). A complex system is defined as a system with numerous components and interconnections, interactions or interdependencies which are difficult to describe, understand, predict, manage, design, and/or change (Bagdasaryan, 2011). Computer modelling is crucial for studying the behaviour of a complex system, these models can be based on the major paradigms in simulation modelling, which are: System Dynamics (SD) and Agent Based Modelling (ABM) (Bagdasaryan, 2011; Borshchev & Filippov, 2004).

SD represents the system as a whole through differential equations, the model consist of variables connected by arrows, where feedbacks, delays, and non-linearity are important (Badham, 2010; J. D. Sterman, 2000). SD derives a dynamical behaviour describing systems as a macroscopic structure (high aggregate level), where components of the system interact among themselves (J. D. Sterman, 2000).

ABM is a modelling technique where the behaviour of many individuals (tens, hundreds, thousands, millions) shows the behaviour of the whole system. Multiple simulations allow determining patterns; this technique can be used for forecasting in social and economic systems (Borshchev & Filippov, 2004; Badham, 2010; Bagdasaryan, 2011). This approach allows to model heterogeneous, autonomous, individual entities (Borshchev & Filippov, 2004a). However, ABM seems more suitable when complex systems exhibit high heterogeneity at the micro level, additionally some have found difficulties to calibrate ABM models (Olsina, 2005).

Econometric models reproduce the actual observed behavior, but in the short-term because this methodology requires a large quantity of data to obtain trustworthy predictions, besides they represent statistically relationships between variables neglecting feedback loops (Olsina, 2005). Econometric models are commonly used to forecasting electricity demand considering the population, economic growth and wholesale prices (Dyner & Larsen, 2001).

Following reasons lead to the author of this thesis to choose SD over other methodologies (Qudrat-ullah, 2015):

First, power systems are subjected to high level of uncertainty, which are fostered by following trends:

- The nature and life of incentives and rules of the market keep changing.
- Technological disruption threat to change everything.
- Prices and availability of fuels are highly volatile.
- Because of deregulation there are “many more” stakeholders who come with conflicting objectives – making energy policy decisions even more complex.

Second, power systems exhibit non-linear relationships. For instance, when electricity price fall then purchase of energy from the industrial sector grows, but if electricity price keeps falling the usage of energy of industrial sector will saturate because reaches its maximum capacity. Non-linear relationships are common in socio-technical systems such as power systems. Therefore, it is necessary to represent them.

Third, power systems are characterized by time delays. For instance, the construction of power plants involves a long process with material delays (the time that takes to build a power plant) and information delays (time of approval of the application and commissioning permit etc). These delays are important to investors and energy planners.

Fourth, causation not correlation and feedback systems are inherent to power systems. The causal nature of the relationship between the variables leads to feedback loops which interact each other and are responsible for the resulting dynamic behavior of the power system. Some studies have already demonstrate the presence of boom and bust cycles in the power industry (Ford, 1999; Ford, 2001). Traditional modelling methodologies are not adequate to provide a feedback-oriented analysis of the energy systems.

5.2 Model description

This research disaggregates the power/distribution assets of a representative company (termed "Company A") from the rest of the utilities, to analyse the effect of renewables on this utility. Company A is a fictitious, vertically-integrated company that is dedicated to the generation, distribution, and sale of electricity to customers (retail business). Following the standard SD approach, the dynamic hypothesis proposed in this research enables the exploration of threats to the Company A by considering different aspects of the penetration of renewables into the electricity system.

The dynamic hypothesis 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.

Figure 14 shows the electricity market dynamics, where capacity margin depends on the difference between electricity demand and installed capacity; when the capacity margin is becoming 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 electricity price (See feedback loop B2). Installed capacity includes the installed capacity of rival companies and that of Company A, which is limited to prevent an overly-concentrated electricity market (See feedback loop R2).

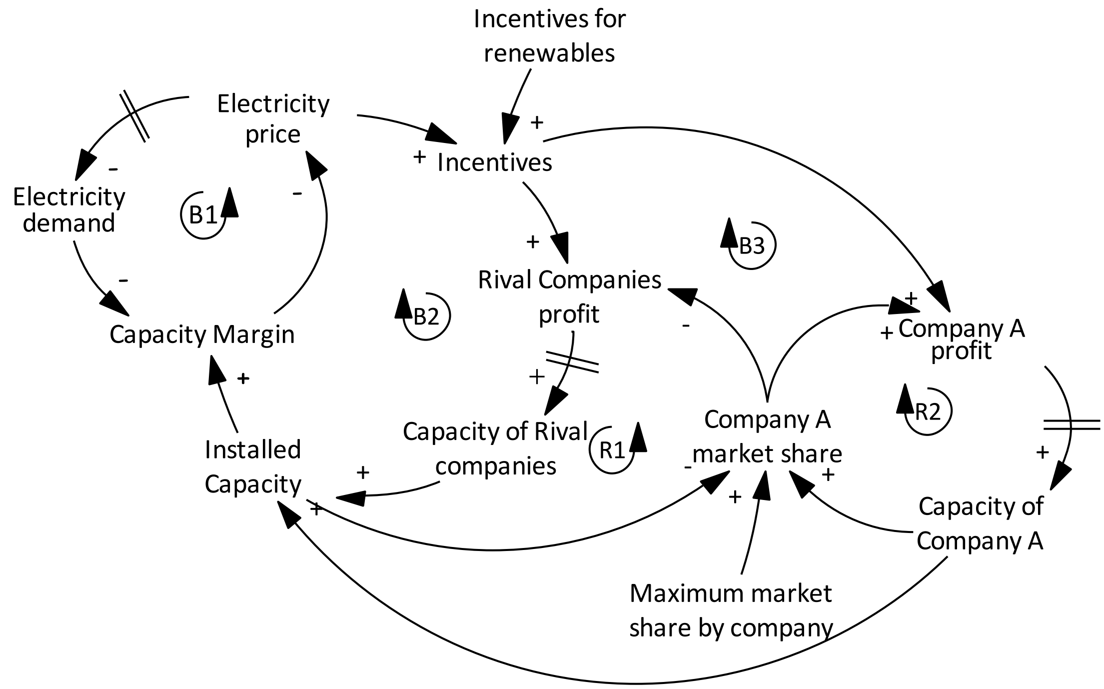

Figure 14. Dynamic hypothesis of the electricity market.

Source: Own elaboration based on Dyner (2000).

The capacity market is a mechanism to ensure the security of supply through investments via capacity auctions. **Figure 15** shows the dynamic interaction of the capacity market and the electricity market. The negative feedback loops, B3 and B4, correspond to the capacity market dynamics. Note that margin represents the excess of available generation capacity to peak demand and is expressed in percentage terms. The future reserve margin depends on the projected installed capacity and expected electricity demand. If the future reserve margin decreases then the difference (between the reserve margin and the desired reserve margin) increases; triggering the capacity auctions, and as a consequence, the reserve margin increases (see feedback loop B3). The auctions also affect the price of electricity, which influences electricity demand and therefore the future electricity demand and reserve margin (see feedback loop B4).

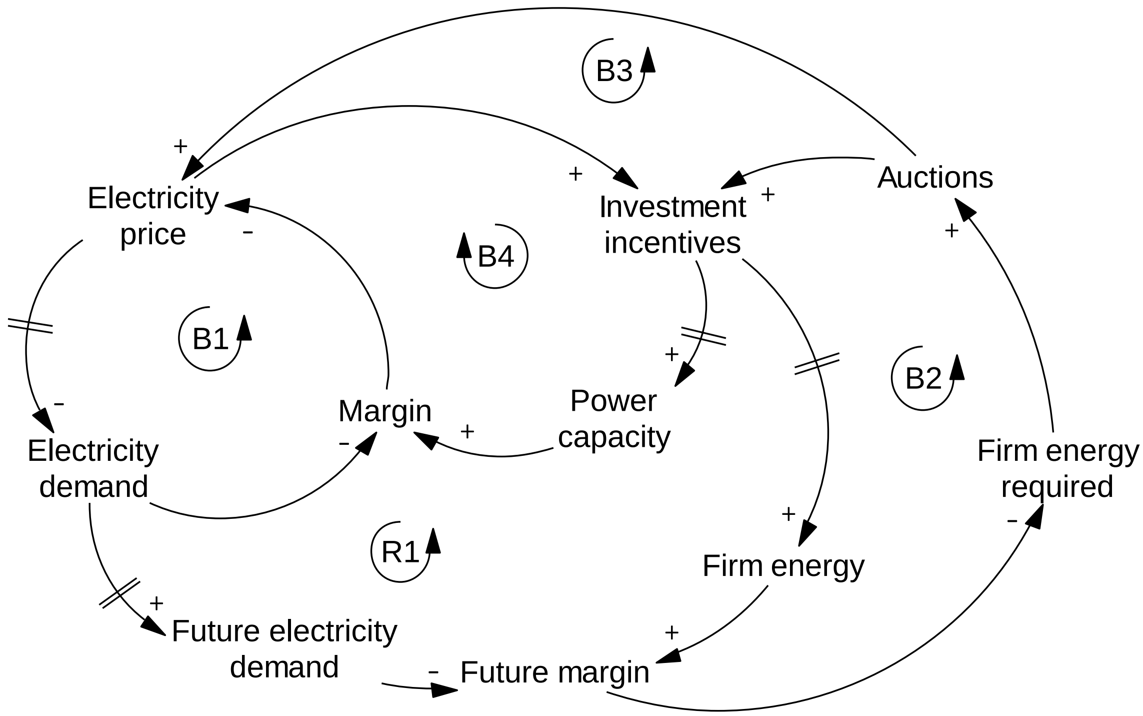

Figure 15. Dynamic hypotheses for the capacity market

Source: Franco et al. (2015)

Figure 16 shows the electricity market dynamics with a specific focus on the diffusion of solar PV systems. The levelised cost of electricity (LCOE) refers to the generation cost of PV-owners. The electricity tariff, paid by consumers, incorporates the following components: electricity generation price, transmission charge, distribution charge, retail charge and other charges. Households compare LCOE alternatives with the electricity tariff to decide on their choice of electricity supply. Learning effects lead to solar PV cost reduction as the number of adopters of PV systems increases (See feedback loop B4). Electricity demand decreases when PV adopters increase, and consequently tariff charges increase to guarantee the economic sustainability of the network, because tariffs are volumetric (See feedback loops R1 and R2). These reinforcing cycles increasingly reduce the number non-PV adopters.

Solar PV knowledge-diffusion is modelled through a Bass model and the economic decision to adopt solar PV systems was modelled through a logit model (Bass, 1969; Dyner & Franco, 2004).

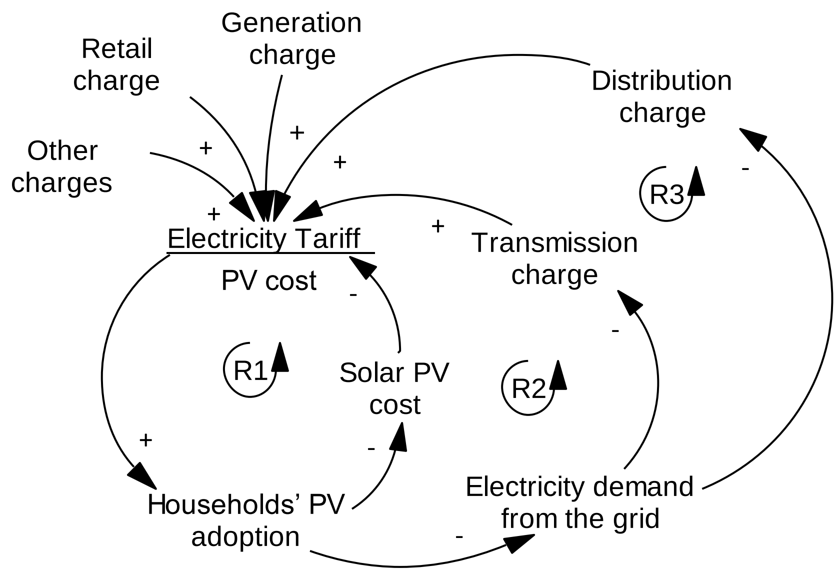

Figure 16. Utility death spiral

Source: Jiménez et al., (2016), Castaneda et al., (2017b)

The electricity tariff EC paid by consumers (Eq. (1)) incorporates the following components: generation charge G (also called electricity price in **Figure 16Figure *16***), transmission charge T, distribution charge D, retail charge R, and other charges that incentivise renewable energies and security of supply (CREG, 1997).

$$EC = G + T + D + R + Other \quad (1)$$

PV diffusion follows the Bass model (Bass, 1969) that considers how information disseminated through potential households translates into PV-adoption. Eq. (2) 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 (Mahajan, Muller, & Bass, 1990):

$$n(t) = \frac{dN(t)}{dt} = p[m - N(t)] + \frac{q}{m}N(t)[m - N(t)] \quad (2)$$

Eq. (3), 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 λ parameter indicating the willingness to choose the PV technology.

$$s_i = \frac{LCOE^{-\lambda}}{LCOE^{-\lambda} + EC^{-\lambda}} \qquad (3)$$

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.

Figure 17 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.

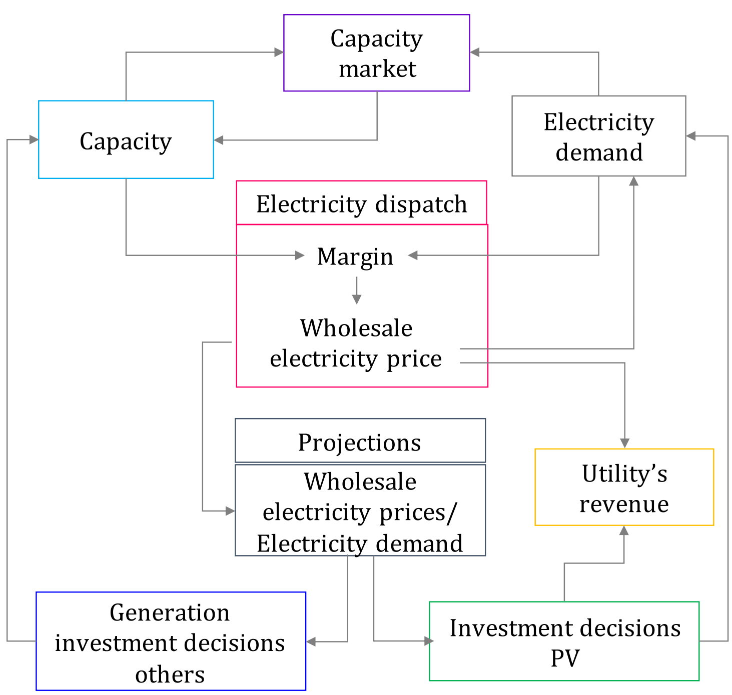

Figure 17. Overview of the SD model

Source: Own elaboration based on (Franco et al., 2015).

Based on the proposed model structure, a formal simulation model was built using the Powersim software, to test the dynamic hypothesis presented in **Figs. 14, 15 and 16.** This broad model structure, previously used to analyse the British electricity market (Franco et al., 2015), 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.

Electricity generation is modeled by an algorithm in Visual Basic which presents the intersection of the supply and demand curves of electricity. Where $\mathrm{G_i(t)}$ is the electricity supply of technology i, $\mathrm{C_i(t)}$ is the supply price of technology i and $\mathrm{PE(t)}$ is the price of marginal electricity determined by the supply price of the marginal technology $\mathrm{C_N(t)}$, that means the latest technology supplying the electricity demand $\mathrm{D(t)}$. Renewable technologies are dispatched at the base as not centrally dispatched plants. The dispatch of electricity is simulated monthly. See following equations.

Minimize:

$$\sum_{t=1}^{t=T}\sum_{i=1}^{i=N} G_i(t) \cdot C_i(t) \qquad (4)$$

$$D(t) \leq \sum_{i=1}^{N} G_i\,(t) \qquad (5)$$

$$PE(t) = C_N(t) \qquad (6)$$

The expected profitability of technologies $\mathrm{\pi_i^e(t)}$, employed as an investment signal is calculated considering the expected price of electricity $\mathrm{PE^e(t)}$, the expected cost of generation of each technology $\mathrm{C_i^e(t)}$. See eq. 7.

$$\pi_i^e(t) = PE^e(t) - C_i^e(t) \qquad (7)$$

If a *Feed-in tariff* is implemented, the expected profitability would depend not on expected price of electricity $\mathrm{PE^e(t)}$ but on $\mathrm{FIT_i(t)}$. See eq. 8.

$$\pi_i^e(t) = FIT_i(t) - C_i^e(t) \quad (8)$$

When annualizing $\pi_i^e(t)$ and bring to present value, the discount rate r, the operating time or useful life T_{oi} and construction time T_{ci} is used getting $\Pi_i^e(t)$. See equation 9.

$$A = \frac{(1+r)^{T_{oi}} - 1}{r(1+r)^{T_{oi}}} \cdot \frac{1}{(1+r)^{T_{Ci}}} \cdot \frac{r(1+r)^{T_{ci}+T_{oi}}}{(1+r)^{T_{ci}+T_{oi}} - 1} \quad (9)$$

$$\Pi_i^e(t) = \pi_i^e(t) \cdot A \quad (10)$$

To calculate the unit cost of investment $CI_{vi}^e(t)$ we took into account the load factor of each technology $fc_i(t)$, the investment cost CI_i in [£/MW]; to calculate the profitability is used $\Pi_i^e(t)$ y $CI_{vi}^e(t)$.

$$CI_{vi}^e(t) = \frac{CI_i}{8760 \cdot fc_{i,t}} \cdot \frac{r(1+r)^{T_{ci}+T_{oi}}}{(1+r)^{T_{ci}+T_{oi}} - 1} \quad (11)$$

$$U_i^e(t) = \frac{\Pi_i^e(t)}{CI_{vi}^e(t)} \quad (12)$$

We modeled the costs of technologies using the levelized cost of energy (LCOE). The costs of non-conventional technologies are projected employing the equation of learning curve presented below:

$$C(t) = C(0) \cdot (Q(t)/Q(0))^{\frac{\log(1-LR)}{\log(2)}} \quad (13)$$

$C(t)$ Cost of technology time t

$C(0)$ Cost of technology time t=0

$Q(t)$ Capacity in time t

$Q(0)$ Capacity in time t=0

LR Learning rate

Below are some of the equations of the capacity market.

$$TC(t) = \sum\sum C_{i,j}(t) \quad (14)$$

$M(T) = \frac{TC(t)-D(t)}{TC(t)\cdot cf\cdot 720\ hours}\cdot 100\%$ [%] (15)

$RC(t+\Delta t) = D(t+\Delta t)\cdot(1+M_D) - \sum\sum[C_{i,j}(t) + CC_{i,j}(t) - DC_{i,j}(t)]$ (16)

$TC(t)$ Total installed capacity

$C_{i,j}(t)$ Total installed capacity where i=1…n corresponds to technologies and j=1, 2 corresponds to the companies or the rest of the market

$M(t)$ Capacity margin

$D(t)$ Electricity demand

M_D Expected capacity margin

cf Capacity factor

$CC_{i,j}(t)$ Capacity in construction where i=1…n corresponds to technologies and j=1, 2 corresponds to the companies or the rest of the market

$DC_{i,j}(t)$ Closing capacity where i=1…n corresponds to technologies and j=1, 2 corresponds to the companies or the rest of the market

$RC(t)$ Required Capacity

For the module of PV investment the following equations are used.

$LCOE_n = \frac{\sum_{t=0}^{T}(I_t+O_t+D_t)/(1+r)^t}{\sum_{t=0}^{T} S_n(1-d)^t/(1+r)^t}$ (17)

$LCOE_t = LCOE_{t=0}\cdot E$ (18)

$E = \left[\frac{Q_t}{Q_0}\right]^{-b}$ (19)

$b = \frac{ln(1-LR)}{ln(2)}$ (20)

b learning index

LR learning rate, cost reduction per doubling of experience

$Distribution\ charge$

$D_t = \frac{DNC}{E_{vt}}$ (21)

$E_{vt} = EM + EN$ (22)

$EM = M \cdot (Z - S)$ (23)

$EN = (TH - M) \cdot Z$ (24)

$Utility\ income = D_t \cdot E_{vt}$ (25)

D_t *distribution charge*

DNC *distribution network costs*

E_{vt} *electricity demand by voltage level*

EM *electricity demand from PV adopters [Households]*

EN *electricity demand from non-PV adopters [Households]*

Z average energy consumption by household

S microgeneration by household

5.2.1 Assumptions

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:

- Capacity expansion in non-conventional technologies is undertaken through an investment function that depends on technology indicators;
- Alternative renewable-based technologies for power generation include: wind, small hydro, biomass, geothermal and, at the residential level, solar PV.
- 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.
- 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.

5.2.2. Stocks and flows

Figure 18 shows the conceptual framework of the SD model in terms of stocks (i.e. power capacity and demand) and flows (i.e. demand growth and capacity investment rate). The capacities of Company A and its rival companies are accounted for two separated stocks. This model provides an easy means for policy assessment; simulation results give users a rapid overview of the long-term impacts of environmental policies and Company A decisions.

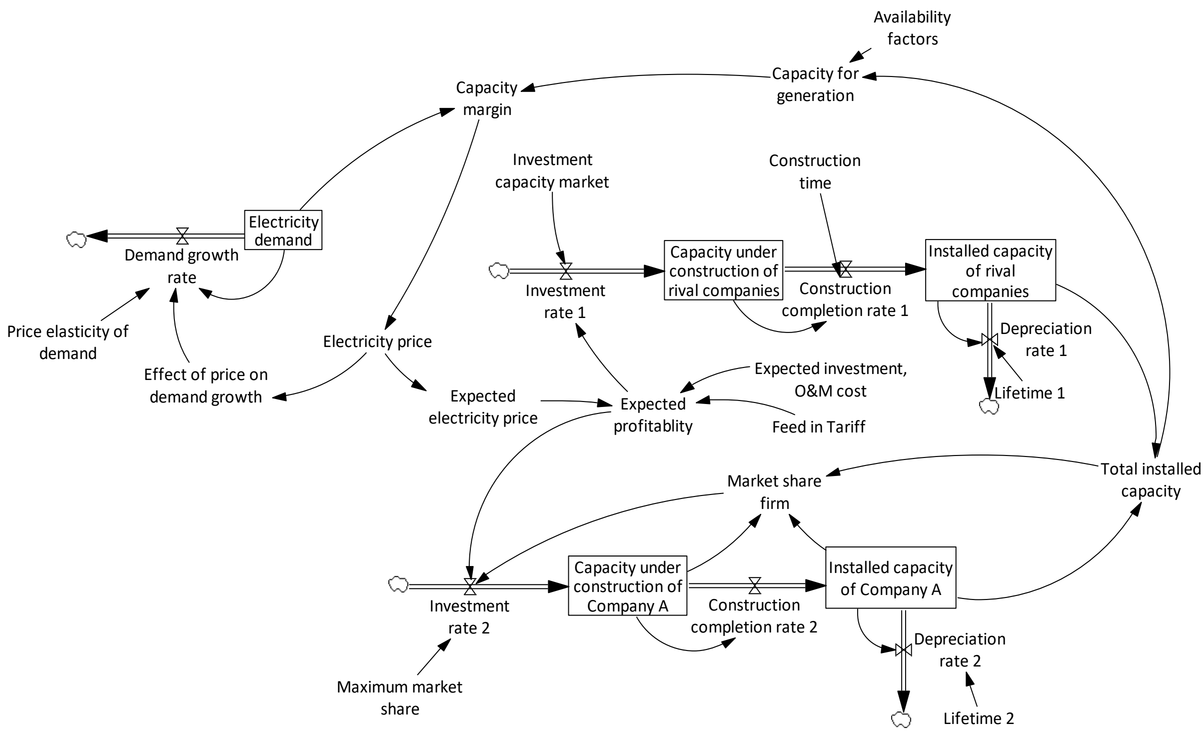

Figure 18. Stocks and Flow diagram part I

Source: own elaboration.

The dynamics of the PV adoption, PV learning curve and rate-setting are depicted in **Figure 19**. “Households” is the unit of analysis used to measure populations of potential adopters and adopters, since a solar PV system usually owns to one family. Potential adopters become PV adopters, through a bass model, as the adoption rate depends on both social contagious as well as on knowledge about PV technology. PV adoption is considered by household customers that live in houses with exclusive rights to the roof. Potential PV adopters increase according to the population growth and new dwellings in place with no PV installations. Households willing to adopt augment by the fraction willing to adopt and population growth. Fraction willing to adopt is a function that compares electricity *PV Cost* and electricity *Tariff* to represent the attractiveness to install PV (John D. Sterman, 2000).

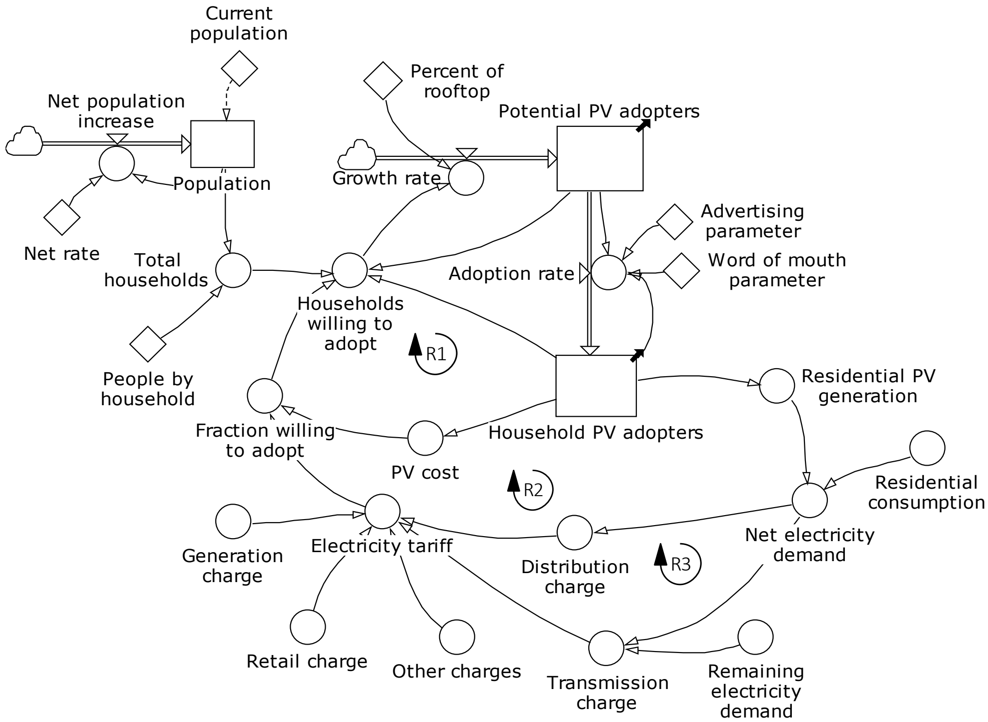

Figure 19. Stocks and Flow diagram part II

Source: Castaneda et al., (2017a)

5.3 Validation

Validation of SD model does not lead to the absolute truth, because as John Sterman once said "all models are wrong" (Sterman, 2002), this means that SD models are a limited representation of the real world. SD models are designed to reach a particular purpose, therefore the validation depends on the objective of the model. Different schemes for validating SD models have been proposed in the literature (Barlas, 1996; Forrester & Senge, 1996; Sterman, 2000) (See **Figure 20Figure *20***), but all these schemes have the same purpose, to valid: model structure and model behaviour.

.

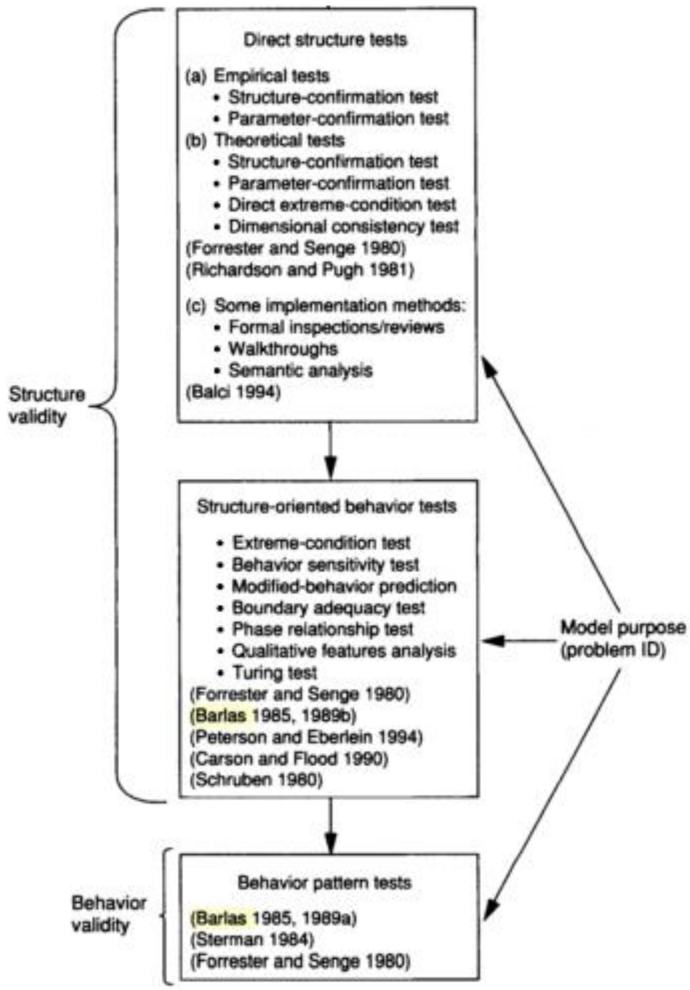

Figure 20. Schemes for validation of system dynamics.

Source: Barlas (1996)

For this research, the validation tests proposed by Sterman (2000) have been carried out, which include following tests:

1. Boundary adequacy
2. Structure assessment
3. Dimensional consistency
4. Parameter assessment
5. Extreme conditions
6. Integration error
7. Behaviour reproduction
8. Behaviour anomaly
9. Family member
10. Surprise behaviour
11. Sensitivity analysis
12. System improvement.

Each test is developed below.

5.3.1 Boundary adequacy.

The model boundary should be defined considering the model purpose. As the main objective of this thesis is to "Develop a framework for assessing electricity utilities strategies, under environmentally friendly policies", this implies that model boundaries may allow to model the merit-order effect and the utility death spiral shown in Chapter 2. A subsystem diagram, causal diagrams and stock and flow maps presented in Chapter 5 are helpful tools to demonstrate that the boundary of the model is adequate. Therefore, the model aggregation is proper and include all the relevant variable that contain the feedback effects inherent to research objective posed here.

To support this statement, the endogenous variables described below are the most important concepts for addressing the problem endogenously.

- Installed capacity - Generation of electricity
- Electricity price.
- Electricity demand.
- Quantity required in capacity market.
- Capacity market payment.
- Distribution charge.
- Investment capacity.

The model was inspected to see if the exogenous variables were adequate. These are mentioned below:

- Peak electricity demand.
- Learning rate.
- Desired Margin.
- Operation, maintenance and investment costs of power technologies.
- Availability factor.
- Power plants under construction in coming years.
- Average power consumption per household.

If boundary assumptions are relaxed or extended the results posed here does not change substantially, for instance, solar PV is mainly adopted in the residential sector but if other sector (industrial and commercial) are considered the results are similar (See Chapter 6).

5.3.2 Structure assessment

This test intends to answer following questions: Is the model structure consistent with the knowledge about the real system? Is the level of aggregation adequate? Is the model aligned to basic physical laws such as conservation laws? And finally, how near the decision rules are from capturing the behaviour of the actors in the systems?

Each equation was checked to verify conformity with physical laws, the results of this inspection demonstrate full conformity with them. Following equations show how careful is the author to define each equation correctly.

Generacion solar=

IF('Decisor excedentes'=0;MIN('Requerimiento Horario por hogar diario'*1<<kW>>/1<<kWh*ho>>;'Capacidad instalada'*'Eficiencia Promedio de los paneles'*'% Radiación solar_hora'/1<<ho*Hogar>>); 'Capacidad instalada'*'Eficiencia Promedio de los paneles'*'% Radiación solar_hora'/1<<ho*Hogar>>)

Distribution charge=

IF(('Ingreso red dbn'[1]/IF('Demanda residencial'[1]<=0<<MW*hr>>,1<<MW*hr>>,'Demanda residencial'[1]))

>='Límite Dt'[1], 'Límite Dt'[1], ('Ingreso red dbn'[1]/IF('Demanda residencial'[1]<=0<<MW*hr>>,1<<MW*hr>>,'Demanda residencial'[1])))

5.3.3 Dimensional Consistency

This test verifies whether all equations are dimensionally correct. First, the model equations were posed considering the units of each variable and balance each side to the equation to guarantee dimensional consistency. Second, the model was built using the computer network facility of the simulation software Powersim Studio 10, which incorporates a dimensional analysis software.

5.3.4 Parameter Assessment

Parameters use in the model along with their numerical values should have real system equivalents. All the parameters used here correspond to real world. As the model was applied to several countries: Colombia, Brazil and UK. The parameters used for each application case are detailed in Chapter 6 when each power market is described.

5.3.5 Extreme conditions

This test means that the model should behave in a realistic fashion under extreme nut possible values of variables. Equations were scrutinized to assess the behavior of variables in extreme conditions. Also, the model was run to verify the behavior under two extreme and possible conditions: (i) Bass parameters get values cloze zero, (ii) Feed-in tariff rate was removed for the Colombian study case (see more about Colombian scenarios in Chapter 6). As expected, Bass parameters take very low values the solar PV cumulative installed capacity in the residential sector is meaningless (see **Figure 21**). Additionally, if any feed-tariff is implemented in Colombia the investment capacity in renewable power technologies such as wind would be slow down (See **Figure 22**).

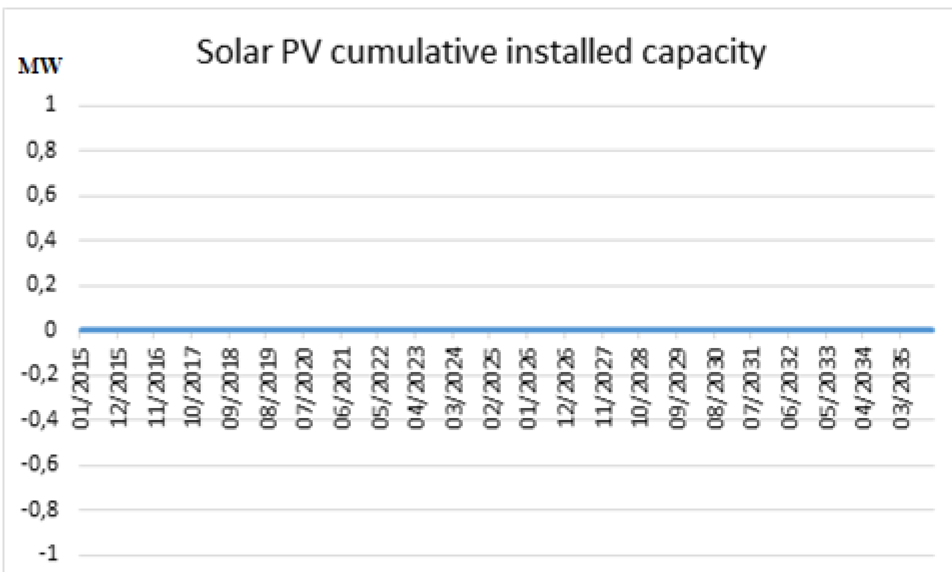

Figure 21. Solar PV installed capacity [MW] in the residential when Bass parameters are near to zero

Source: Authors.

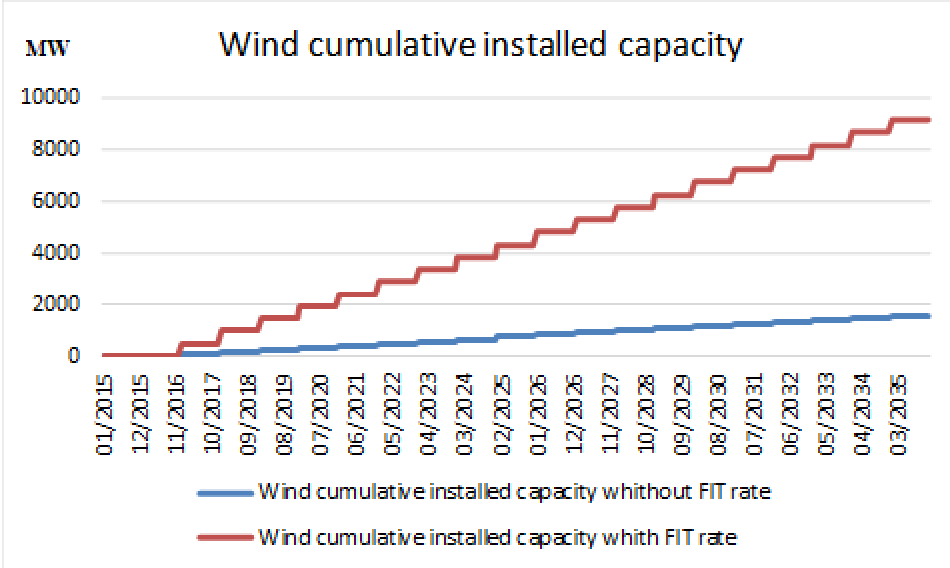

Figure 22. Wind installed capacity [MW] with and without FIT rate.

Source: Authors.

5.3.6 Integration error

Test on integration error should show that results are not so sensitive to the choice of time step or numerical integration method. All the simulation results shown in this thesis run under Euler method. **Figure 23** presents the total cumulative installed capacity of Colombia using two integration methods: RK4 and Euler, as can be observed the difference of using this integration methods is negligible.

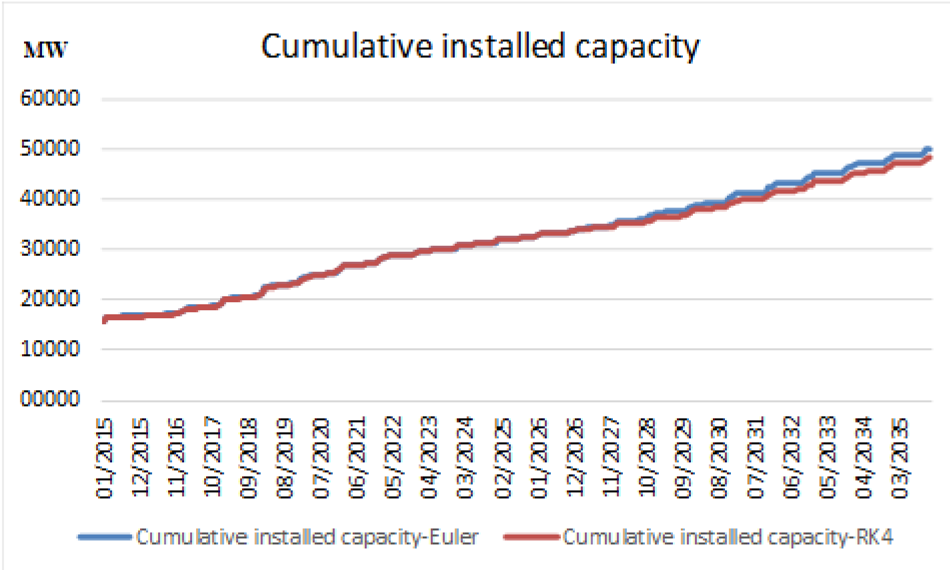

Figure 23. Cumulative installed capacity using different integration methods.

Figure 24 and **Figure *25*** show the cumulative installed capacity using monthly and daily time steps respectively, the results are not very different. In fact, with a monthly time step the cumulative installed capacity by the end of 2035 is 50MW, while with a monthly time step the cumulative installed capacity by the end of 2035 is 48MW.

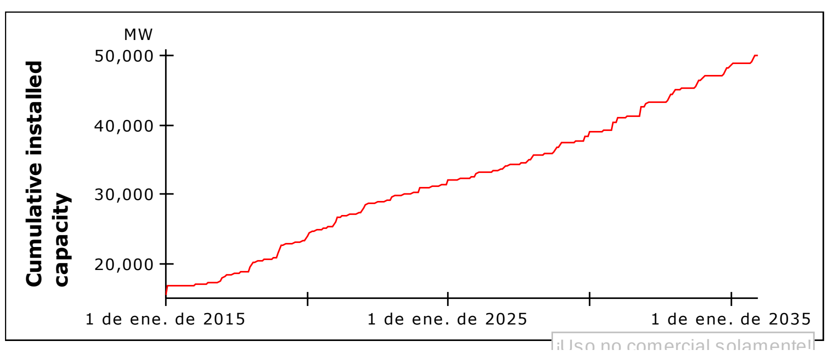

Figure 24. Cumulative installed capacity using a monthly simulation time step.

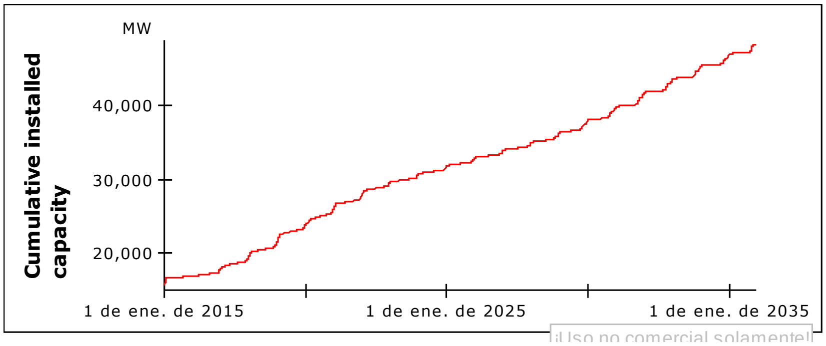

Figure 25. Cumulative installed capacity using a daily simulation time step.

5.3.7 Behavior reproduction

If this test is passed, means that the model generates the mode of behavior observed in the system, the model behavior is compared with the historical behavior to verify if the model behaves in the same way the system does. For this test, it was used the UK application case, the reason is that this country has already implemented many of the policies proposed here for Colombia, therefore there is enough historical data. **Figure** ***26*** demonstrates that model generated matches observed behavior of the real system in terms of solar PV adoption in the UK domestic sector.

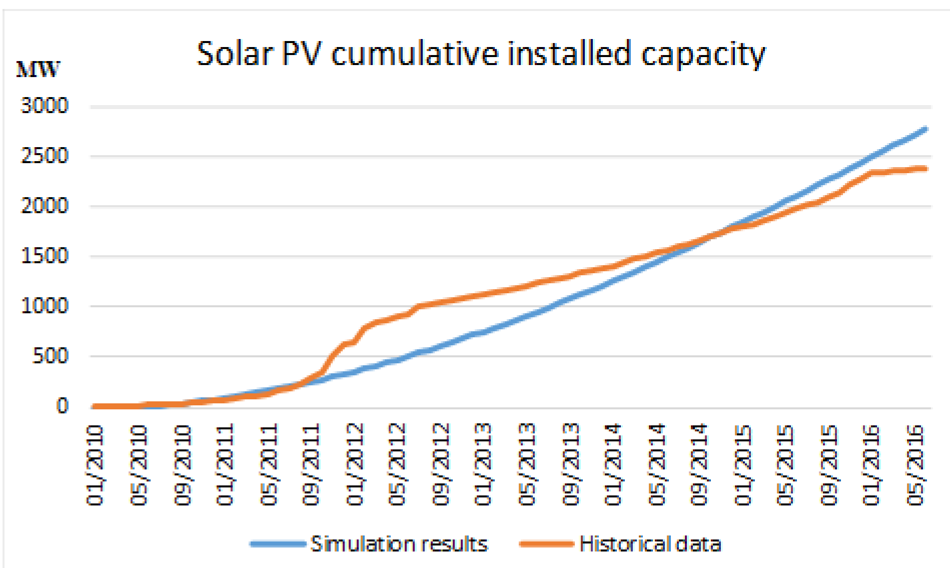

Figure 26. Simulation results of solar PV installations (lower than 4kW) from 2010 to 2016.

*Bass parameters used are p=0.01 and q=0.01

5.3.8 Sensitivity Analysis

A sensitivity analysis explores if behavior change in ways important to your objective when assumptions are changed within plausible range of uncertainty. According to Sterman (2000), there is three types of sensitivity: Numerical, Behavioral and policy sensitivity; these are described next.

Numerical sensitivity: it entails to vary numerical values that are subject to uncertainty. In this model, there are several uncertain variables, for example: the availability factor of power plants, construction time of power plants, the average energy consumption by household, the sunshine hours, the PV system size, etc. A sensitivity analysis was carried out with only two of these variables for Colombian application case, for being the most uncertain variables subject to change. These variables are: average PV system size per household and availability factors of power plants. **Figure 27** shows the range that solar PV cumulative installed capacity will fall with 90% of probability, besides solar PV installed capacity is sensitive to changes in the PV system size. This was to be expected because solar PV installed capacity is equal to PV system size (constant variable) multiplied by the number of households that have decided to adopt. As you can see in the **Figure 28**, the total cumulative installed capacity is not very sensitive to changes in availability factor of power plants, as the difference between 10% percentile and 90% percentile is small (this is expected because investment capacity is mainly affected for electricity price).

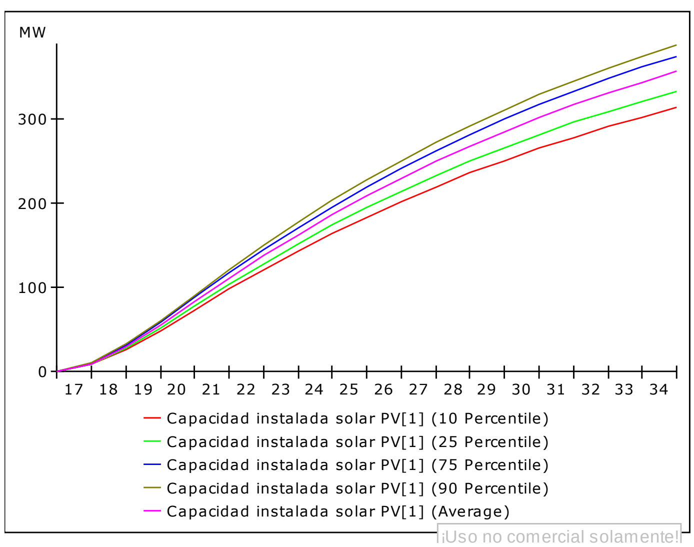

Figure 27. Solar PV cumulative installed capacity vs time period – Sensitivity analysis of PV system size

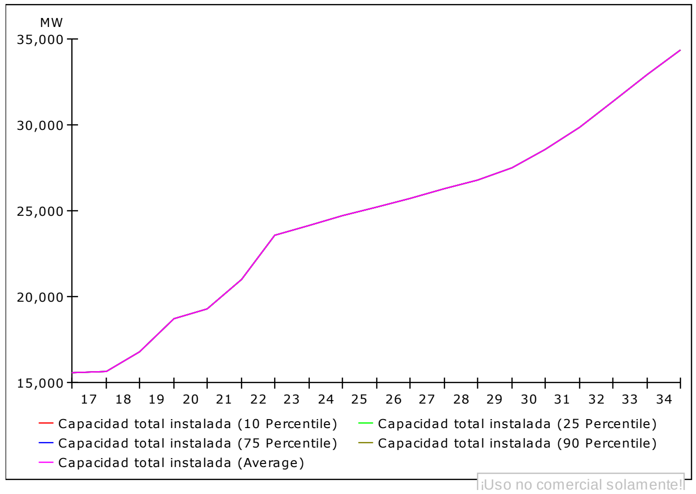

Figure 28. Cumulative installed capacity vs time period – sensitivity analysis on availability factor of power plants.

5.4 Conclusions

In this study, it was built a simulation model based on system dynamics methodology. Though, there are a number of methods that might be considered for this study, system dynamics was chosen because the research problem posed is characterized by feedback cycles, delays and non-linearities. Traditional methodologies such as econometric or optimization model are limited to reflect these characteristics. Furthermore, system dynamics allows to represent the situation in a compact manner and the interest of this research was not to model individual behavior, that is the reason for discarding agent-based modelling.

System Dynamics (SD) models provide a stylised representation of the dynamics features inherent in complex systems, such models aim to support decision process and devising strategies (J. D. Sterman, 2000). The validation process of SD model is required to build confidence in the simulation model, model validity is conferred after applying a stringent methodology that includes structural and behavioural tests (Barlas, 1996; Qudrat-Ullah & Seong, 2010). Several tests were performed in this research for validation purpose. Furthermore, structure-oriented behaviour tests were also accomplished. Firstly, extreme values were given to selected parameters to verified pattern behaviour. Later, a behaviour sensitivity test allowed to confirm a high sensitivity of following parameters: cost of solar PV, end-consumer electricity tariff, size of PV system, and solar radiation, such sensitivity is in accordance with the real system. Thus, the simulation model passed successfully the validation tests, being good enough for the purpose of this research.

Part III. Application cases

Chapter 6. Results

6.1 Colombia

6.1.1 Description of Colombian electricity market

For studying the effect of technology transformation on the 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 (Schmidt et al., 2016). Thus, this paper considers the Colombian electricity market, which is characterised by a high share of hydropower resources combined with some thermo-power dependence.

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 (E. R. Larsen, Dyner, Bedoya V, & Franco, 2004). 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) (Pérez & Osorio, 2002; UPME, 2005; XM, 2015). Additionally, the government has taken an important step to support the development of renewable energies, through Law 1715 (Congreso de la República de Colombia, 2014).

This involves risk, considering that: i) sustained growth in electricity demand could lead to power shortages due to droughts caused by El Niño phenomena (E. R. Larsen et al., 2004); 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 25USD/MWh, which, given the logistical expenses, makes it unsustainable as the system price peak is not much higher than 15USD/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 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 (Congreso de la República de Colombia, 2014).

6.1.2 From the utility perspective

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 1,881 MWs, as indicated in **Table 6**. 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.

Table 6. Installed capacity of Company A and Colombia.

	Installed capacity of Company A[MW]	Total installed capacity in Colombia[MW]	Share of Company A in total installed capacity [%]
Gas	770	3,490	22%
Coal	0	1,016	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	1,881	15,577	12%

Source: Own elaboration based on (XM, 2015).

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 (2015); availability factor and load factor of technologies, from XM (2015); average consumption and electricity tariff, from SUI (2015); and, population and number of households, from DANE (2015).

6.1.2.1 Scenarios

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 (Dyner & Larsen, 2001). 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 (Quiceno et al., 2017). The four scenarios shown in **Figure 29** 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.

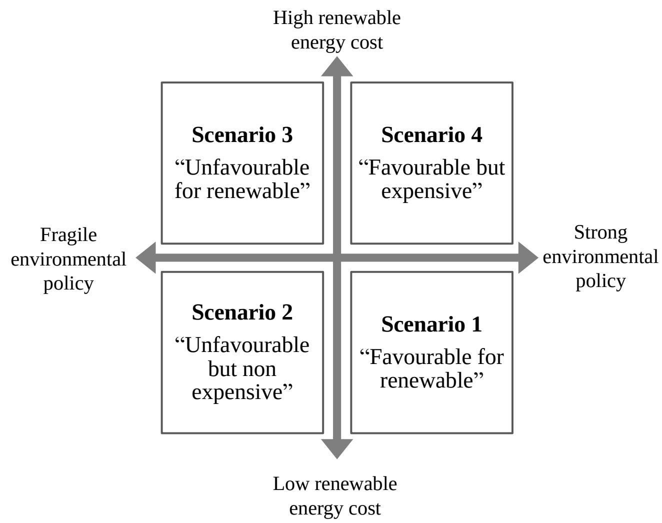

Figure 29. Scenarios for analysing renewable energy impact on a utility.

Source: Own elaboration based on (Quiceno et al., 2017).

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 (Couture & Gagnon, 2010) – 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 7** indicates the cases where FIT and investment subsidies are implemented.

Table 7. Financial incentives applied to each technology during the simulation.

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

Source: Authors.

6.1.2.2 Results for Colombia

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.

6.1.4.1 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.

Figure 30 shows wholesale electricity prices under different scenarios. Initially, prices drop due to the launch of 2,400 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 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 80USD/MWh by the end of the simulation period (see **Figure 30Figure *30***). 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 (Rathmann, 2007).

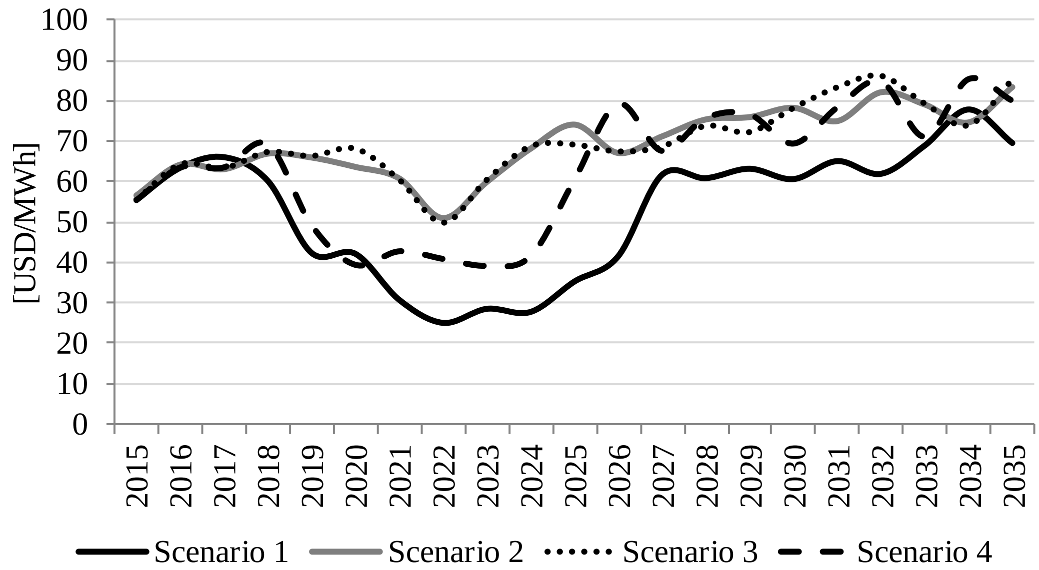

Figure 30. Wholesale electricity price.

Source: Authors.

Figure 31 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% (4,456 GWh/month) by 2035 for the most favourable market conditions and about 16% (1,923 GWh/month) under the most unfavourable market conditions (see **Figure 31**); solar PV electricity contributes about 13% (1,655 GWh/month) to Colombia's electricity supply from 2025 to 2035, under scenarios 1 and 4.

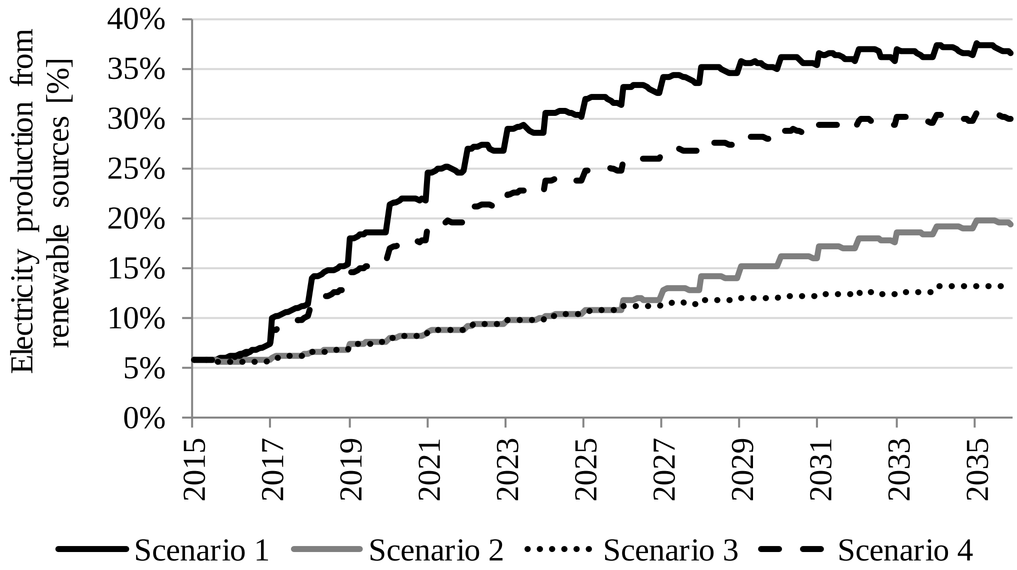

Figure 31. Share of RES in electricity generation.

Source: Authors.

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).

6.1.4.2 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**. Figure 32** 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, **Figure 32** 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.

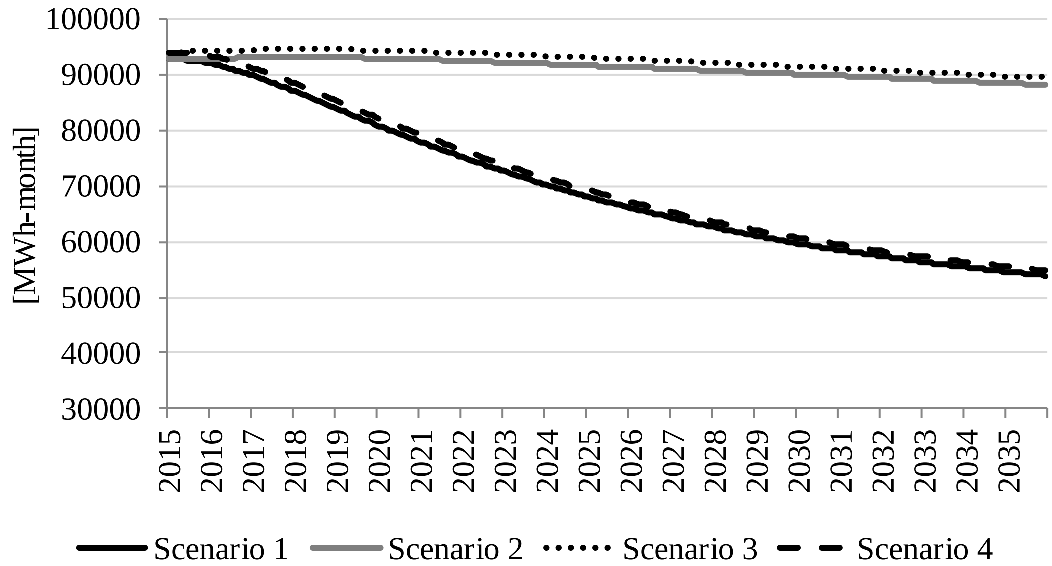

Figure 32. Electricity sales of Company A to the residential sector.

Source: Authors.

Figure 33 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.

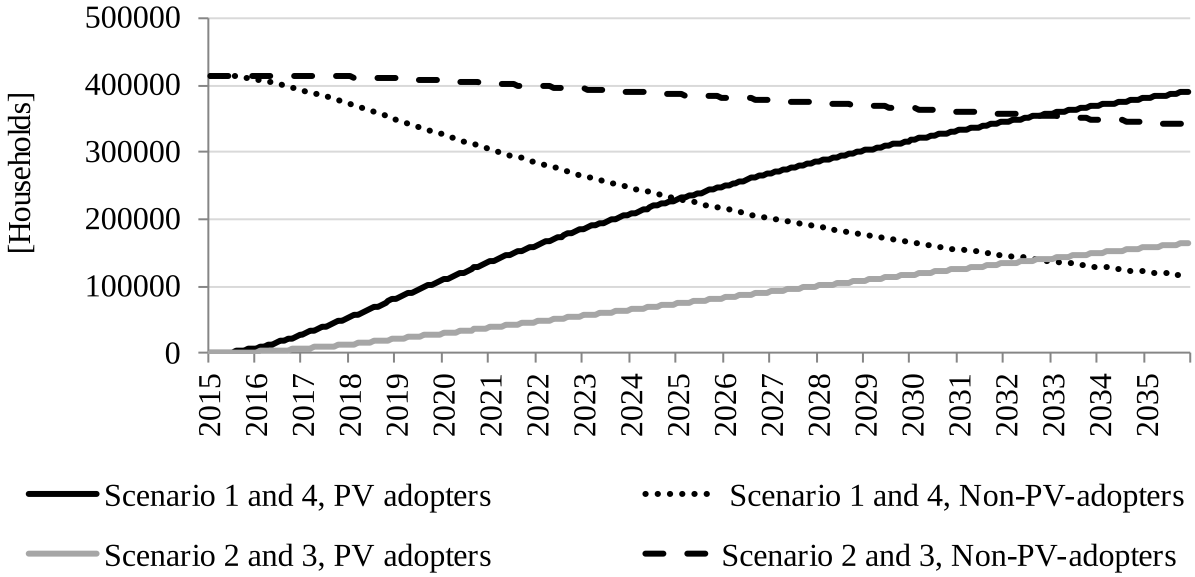

Figure 33. PV adopter vs Non-PV-adopters.

Source: Authors.

As shown in **Figure 34,** 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. (Sensfuß et al., 2008).

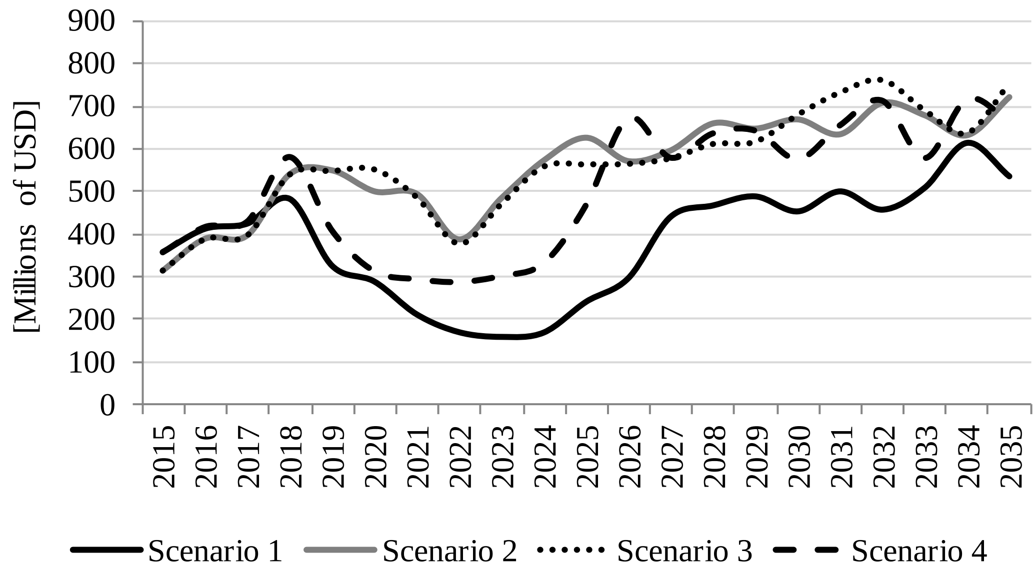

Figure 34. Indicative profits of Company A from its generation business.

Source: Authors.

Figure 35 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 (4,400 MW of rooftop solar PV by 2035). For these scenarios the effects of solar DG on utilities seem modest, coinciding with Satchwell et al. (Satchwell et al., 2015a), but a more prominent scenario is analysed in the next section.

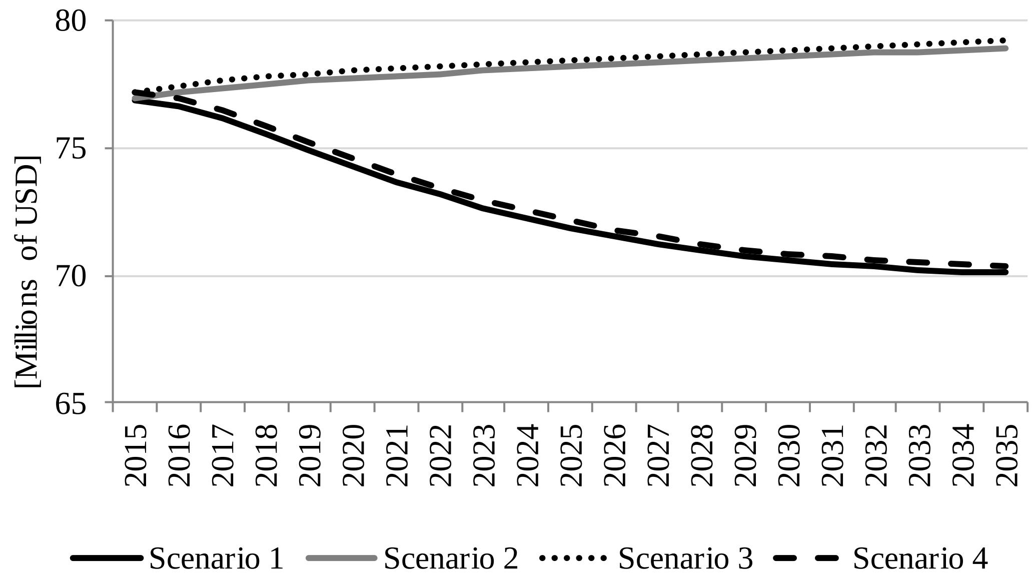

Figure 35. Revenues of Company A from distribution and retail business.

Source: Authors.

6.1.4.3 Effect of an intensive solar PV deployment policy

Solar PV capacity for the least and the most favourable scenarios ranges from 4,400 MW to 10,600 MW, respectively. In the previous scenarios, each PV adopter has a system size of 1kW. For the network area of company A,on average, a household consumes 224 kWh per month. Therefore, with a system size of 1kW the panel would generate 150 kWh per month, (1kW*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. **Figure 36** and **Figure *37*** show that for a 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.

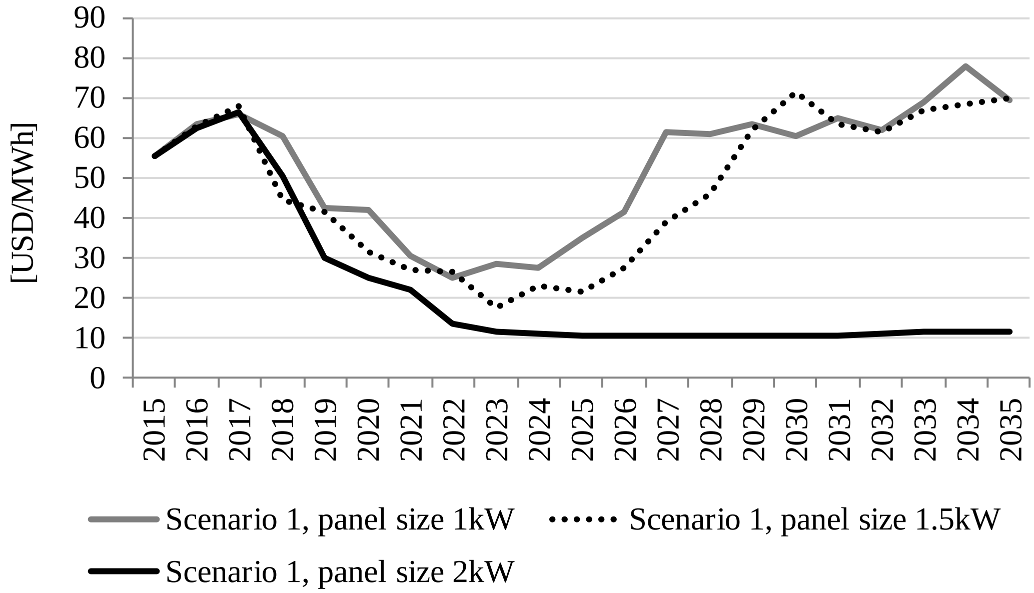

Figure 36. Annual wholesale electricity price for scenario 1 under different levels of PV expansion.

Source: Authors.

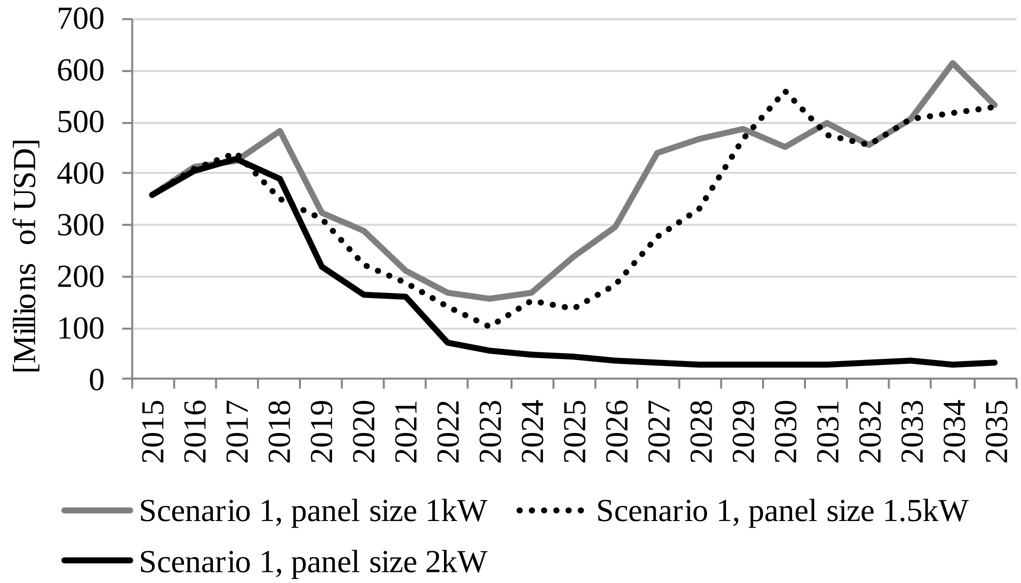

Figure 37. Indicated profitability from the electricity generation business of Company A, for scenario 1 and different levels of PV expansion.

Source: Authors.

With a system size of 2KW, 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 **Figure 38**). Similar behaviour is experienced for the electricity tariff, which includes the transmission and distribution charges.

Figure 39 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.

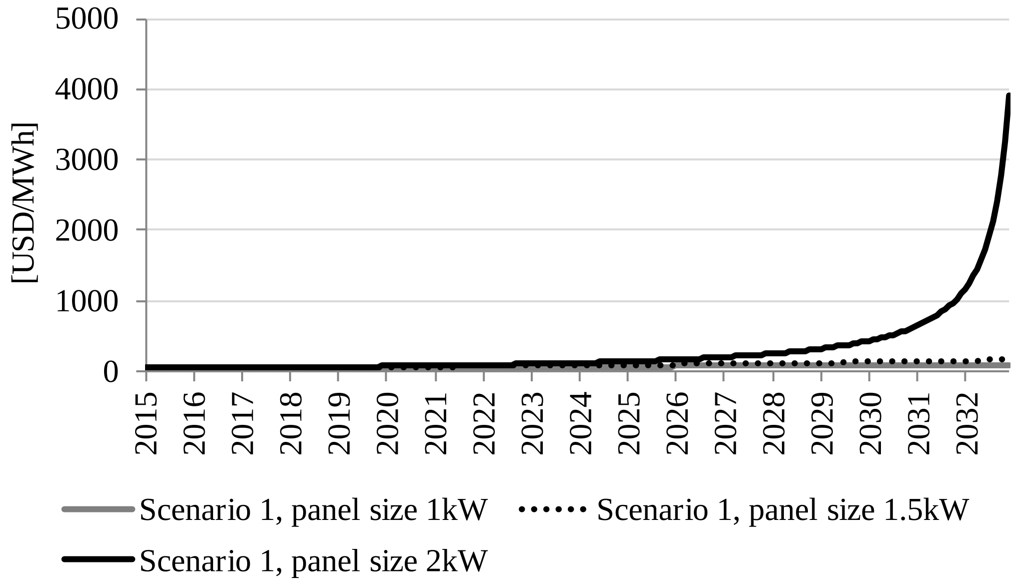

Figure 38. Distribution charge of Company A, for scenario 1 and different levels of PV expansion.

Source: Authors.

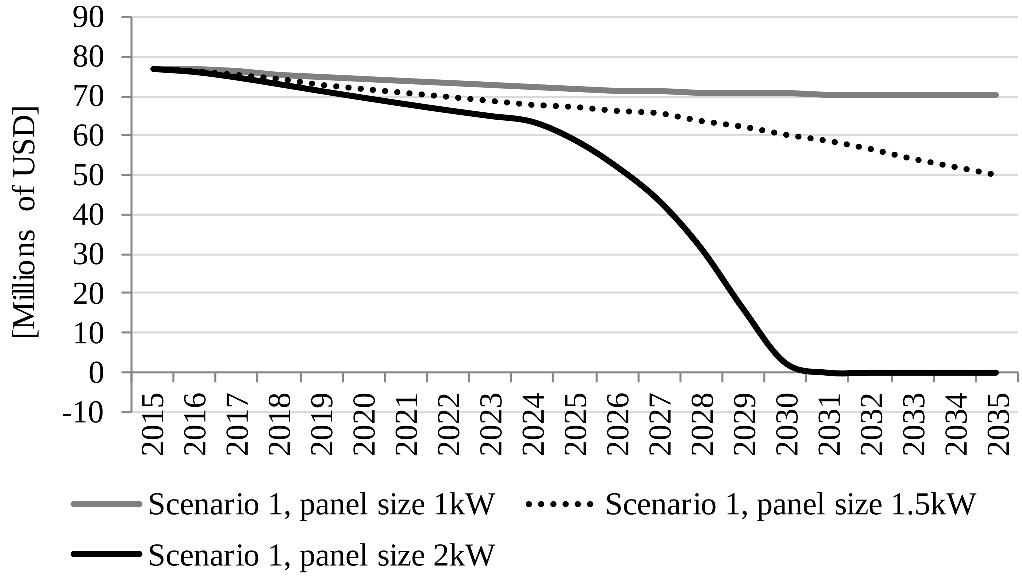

Figure 39. Company A's profitability from electricity distribution and retail business, for scenario 1 and different levels of PV expansion.

Source: Authors.

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 8** 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 minimum 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 0.20 USD/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 2kW, the 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 1.5KW, as shown in **Table 8.**

Table 8. Financial impacts on non-PV-adopters of different solar PV deployment.

	Scenario 1 panel size of 1kW, dates at 2035	Scenario 1 panel size of 1.5kW, dates at 2035	Scenario 1 panel size of 2kW, dates at 2033**
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)	0.20USD/kWh	0.30USD/kWh	6USD/kWh
Expense on electricity by a non-PV-adopting household	134kWh x 0.20USD/kWh=27USD	134kWh x 0.30USD/kWh=40USD	134kWh x 6USD/kWh=804USD
Monthly income of lowest income household (USD)	214USD***	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

**These are the final values; beyond year 2033 the electricity system collapses.

***Minimum income received by an employee.

Source: Authors.

Sensitivity analysis is undertaken in this research 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 9**.

Table 9. Financial impacts on non-PV-adopters of differing solar PV deployment with different assumptions

	Scenario 1 panel size of 2kW**, dates at 2035	Scenario 1 panel size of 2kW with special conditions***, dates at 2035
Solar PV cumulative installed capacity*	9,030MW	19,843MW
Energy consumption by household	134 kWh	134 kWh
Grid Tariff (USD)	0.19USD/kWh	1.73USD/kWh
Expense on electricity by a non -PV-adopting household	134kWh x 0.19USD/kWh =25USD	134kWh x 1.73USD/kWh=232USD
Monthly income of lowest income household (USD)****	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

**Under this scenario 30% of households adopt solar PV systems by 2035

*** Under this scenario 30% of households and 49% of small companies adopt PV systems by 2035.

****Minimum income received by an employee.

Source: Authors.

Table 8 Table **9** 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 research 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.

6.1.2.3 Deeping solar PV effects from the regulator, utility and customers perspective.

As part of this thesis a latter study was carried out to deep the solar PV effects on power industry, but this time the electricity utility industry was analysed as a unit (see more here Castaneda, Jimenez, et al., (2017)). Results obtained from this research corroborate results of earlier research (when a company is disaggregated).

6.1.3.1 Results

As the utility industry is modelled as a whole, the assumption of the PV system size that could lead to a death spiral was relaxed. Under these new circumstances, the model reacts leading to a death spiral when the PV system size is 3 kW. In general, the main assumptions of this model were:

- PV diffusion is limited to the residential sector (a very conservative scenario for the penetration of PVs)
- Net-metering is in place
- The size of the PV systems adopted by households remains invariable during the simulation period and it ranges between 1 kW and 3kW
- Battery storage is not included
- Customer consumption pattern is not modified during simulation runs.
- No new investments are undertaken in distribution network assets

Results suggest that the market conditions that may lead to the utility death spiral are: PV grid parity, net metering, volumetric charge and oversized PV systems.

Figure 40 and **Figure 41** show that the system collapses in 2035, since the total solar PV production minus the total energy consumption falls dramatically in the residential sector for hypothetical case.

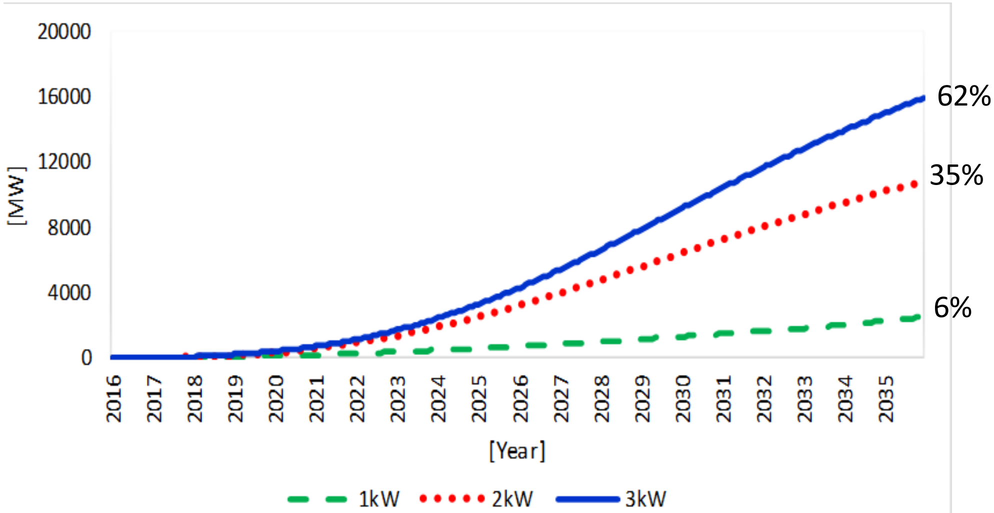

Figure 40. Solar PV cumulative installed capacity and percent of cumulative installed capacity.

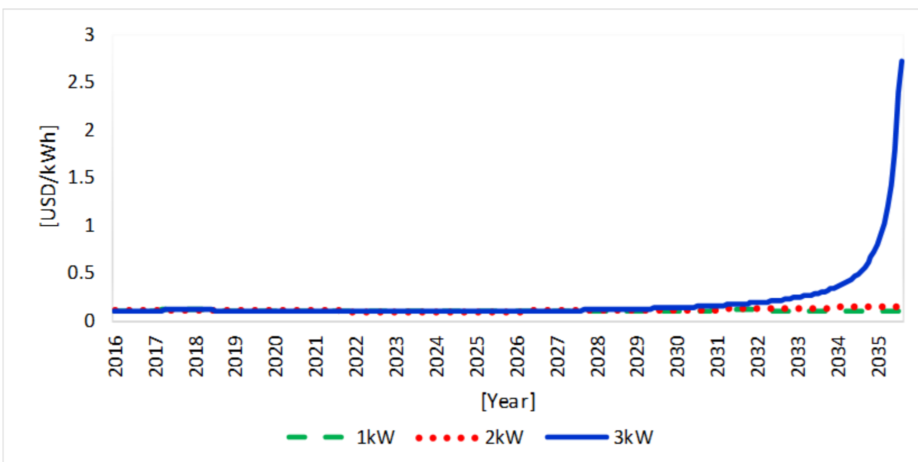

Figure 41. Final tariff for residential sector

A secondary effect is that net metering may lead to free-riding (when PV customers pay less than their fair share of utilities' fixed costs). Revenue losses of utilities coincide with the high expenses of non-PV adopters and high revenues of PV adopters. **Figure 42** depicts the energy bill for both PV adopters and non-PV adopters when the average PV panel capacity is 3kW. 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 **Figure 42**, where in addition, the PV adopter has surplus power during the simulation time. As can be noted, the scenario displayed in **Figure 42** 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.

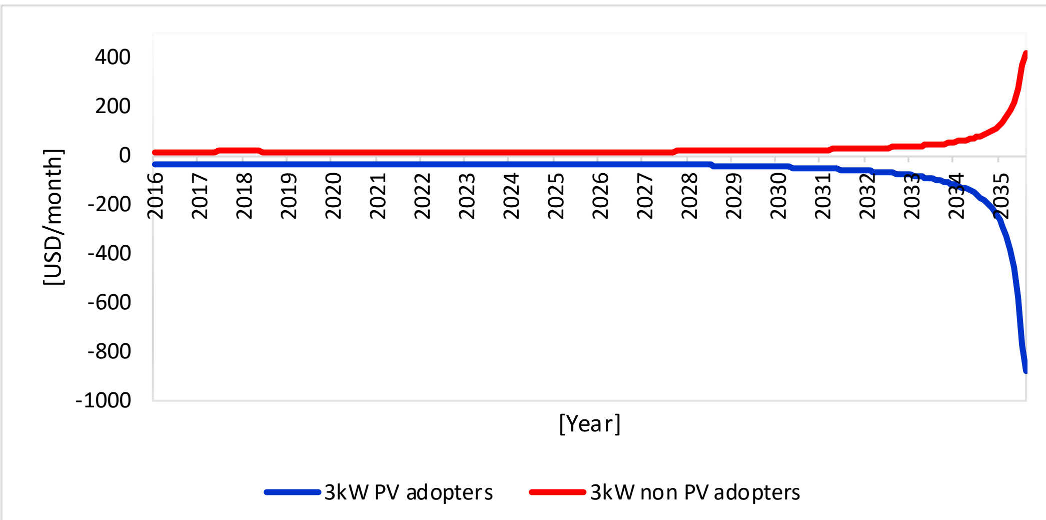

Figure 42. Energy bill for customers under oversized PV systems (3kW)

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 & 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 **Figure 42**). 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 3kW 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., 2016). In addition, **Figure 43** suggests a scenario of economic progress for households where they remain with oversized PV systems (1.7kW per household), after a longer timeframe (2016-2060); this intermediate scenario shows the unfeasibility for utilities through a growing residential tariff.

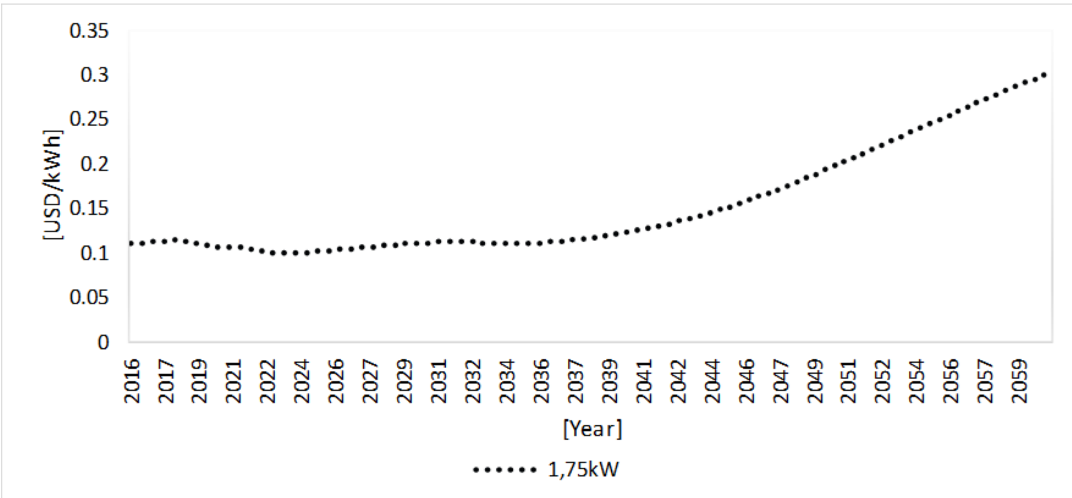

Figure 43. Residential tariff for 1.7kW PV panel size and a longer timeframe

6.1.3.2 Simulating alternatives to mitigate negative effects

Though in subsection 6.1.2 was demonstrated that death spiral is a phenomenon that requires the complete absence of regulator in decision making. The analysis proposed here includes the highest solar PV penetration possible, thus measures to mitigate death spiral are robust if they work well under this extreme scenario. The alternative actions to face the transition toward renewables implemented here were deeply analysed in Chapter 3. These alternative actions are: Implementing a back-up fee, Shifting from Net Metering to Net Billing and Changing tariff design.

A back-up fee internalizes the cost for PV adopters reducing the willingness to adopt. Therefore, it was simulated by increasing PV cost in a 25% and 50%, it was assumed that the increasing in costs financially equivalent to the back-up fee.

Figure 44Figure *44* 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. **Figure 45** presents the residential tariff associated with each level of PV penetration, which is shown in **Figure 44**, 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.

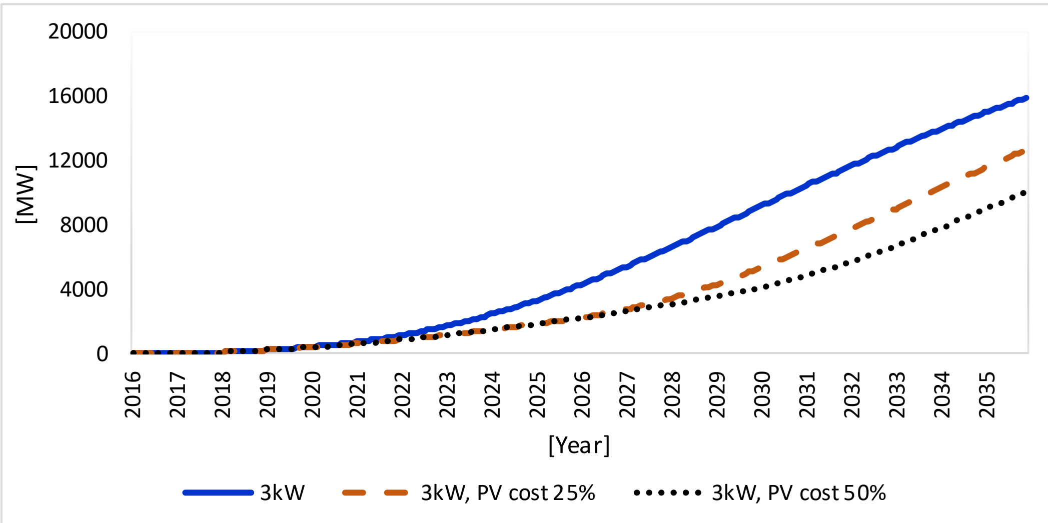

Figure 44. Sensitivity analysis of PV installed capacity under different levels of electricity PV cost

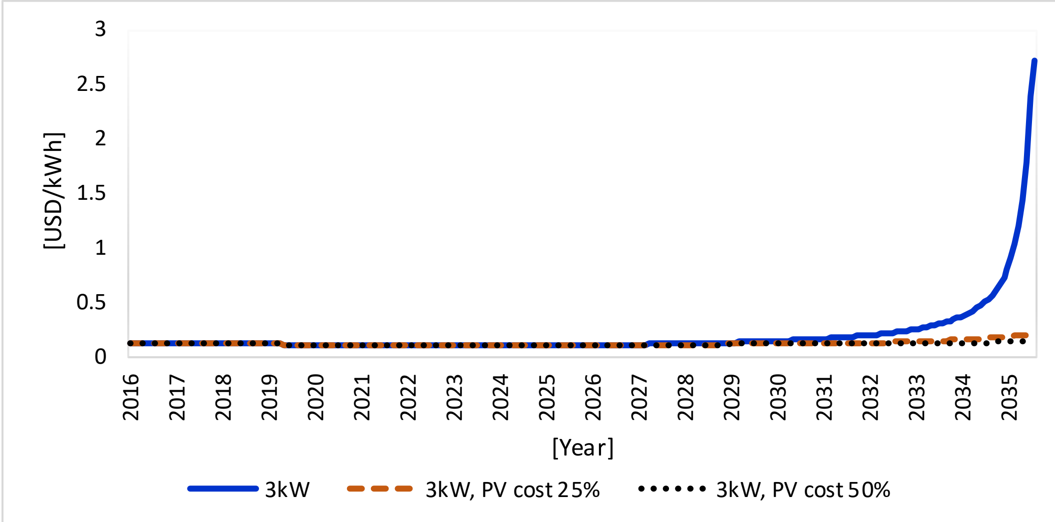

Figure 45. Sensitivity analysis of residential tariff under different levels of electricity PV cost

Shifting from net-metering to net billing means to reduce the compensation for PV energy exported to the grid. **Figure 46** 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. **Figure 46** shows that 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.

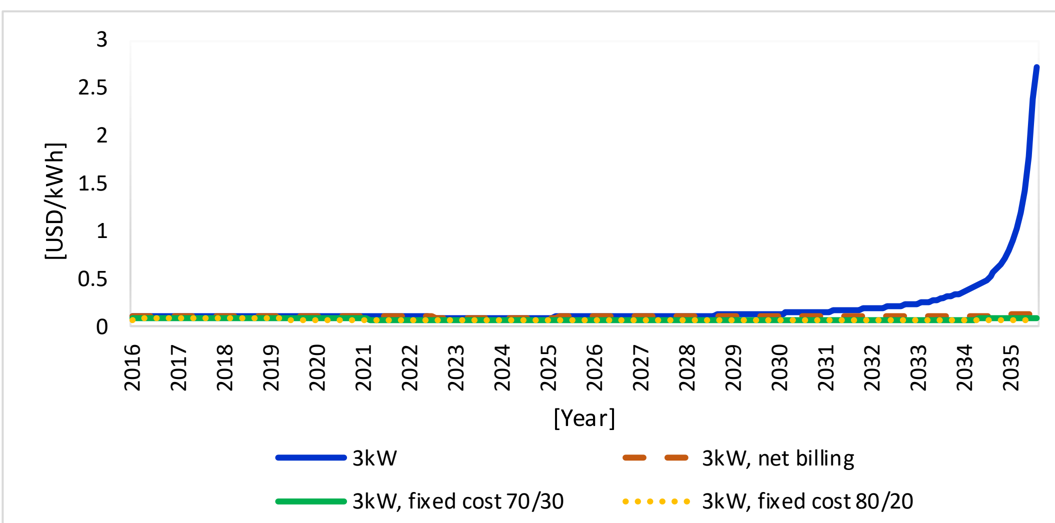

Figure 46. Residential tariff under different tariff designs.

Table 10 shows that the scenario with a 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 research 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.

Table 10. Effects of policy interventions on PV deployment, customers and utilities

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**
3kW reference scenario	15,918	62%	18.4%	18.4%	0%
3kW PV cost 25%	12,693	44%	3.3%	3.3%	85%
3kW PV cost 50%	10,134	32%	1.3%	1.3%	100%
3kW Net Billing	9,142	28%	1.4%	1.1%	100%
3kW fixed cost 70/30	10,783	35%	1.4%	1.1%	100%
3kW fixed cost 80/20	9,661	30%	1.4%	1.1%	100%

6.1.2.4 Measuring the impact of new business models on utilities

The impact of new activities/businesses on utilities are modeled for the two extreme scenarios, scenario 1 and 3. These are:

- Solar PV for large consumers (industrial and commercial sector). Represents the distributed generation
- ESCOs
- Electric cars

The activity/business "ESCOs" represents a reduction on electricity demand, while "electric cars" represents an increase. The spread of electric cars applies only to Antioquia.

Solar PV installed capacity for the industrial and commercial sectors amounts to 4580 MW by 2035, and represents 11% of the total installed capacity of the system. Atlantic Coast, Antioquia, and the rest of the country represent 17%, 10% and 73% of solar PV installed capacity for large consumers (see **Figure 47**). The self-generation for industrial and commercial sectors represent up to 17% of system demand. The energy savings produced by the implementation of ESCOs is around 6000GWh in 2035 (see **Figure 48**).

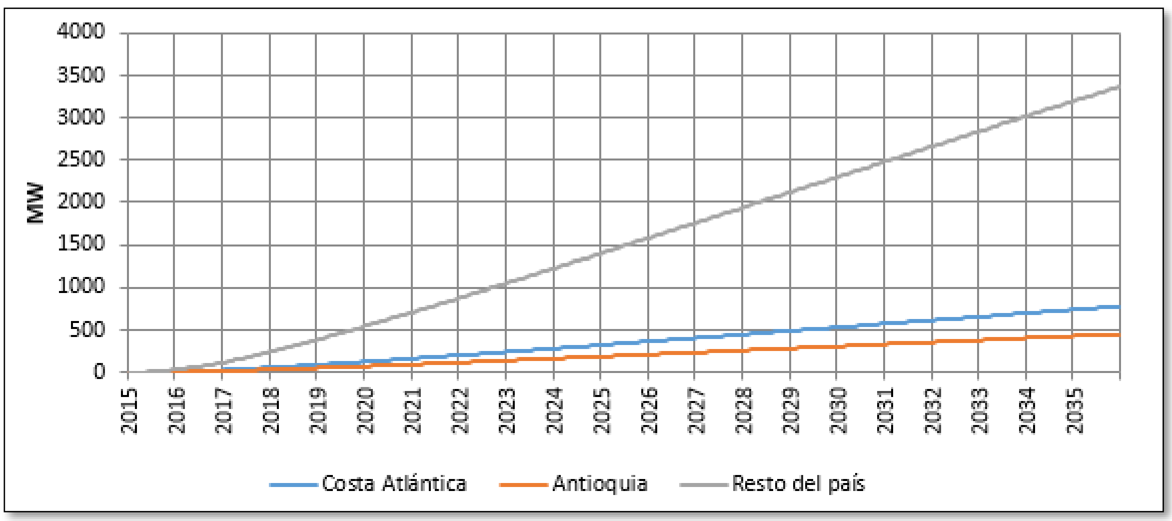

Figure 47. Solar PV installed capacity.

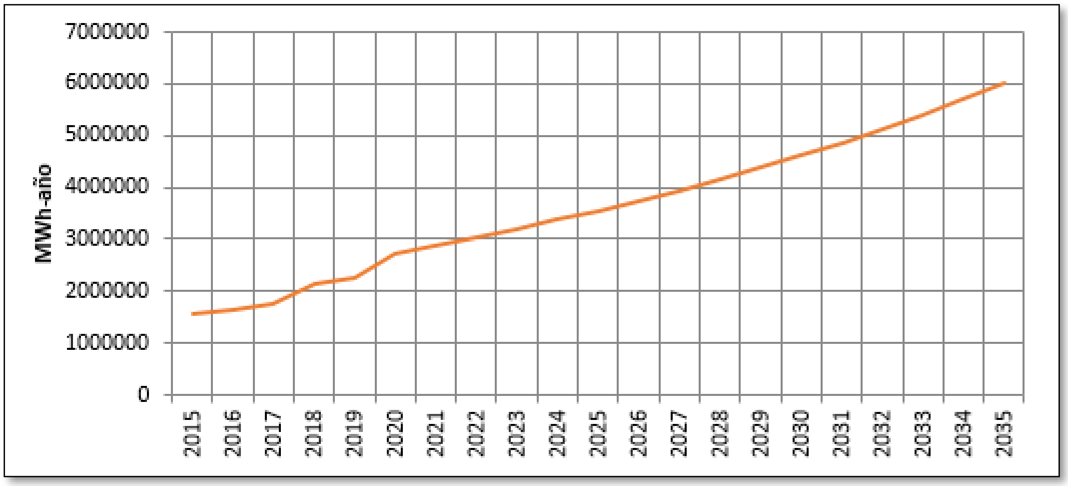

Figure 48. Energy saving through ESCOs

The consumption of electric cars represents 1% of the demand from the SIN. This corresponds to 2.000.000 electric cars in 2035 (see **Figure 49**).

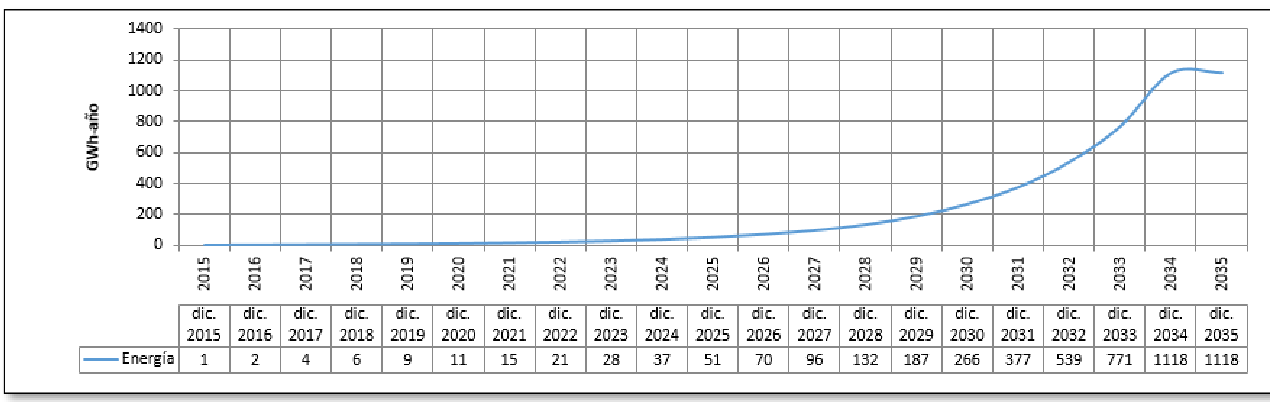

Figure 49. Energy consumption from Electric cars.

ESCOs activity/business is the best one initially, however this is quickly sealed. The solar PV business is the best business in the medium term, while the electric cars business is the best business in the long run.

In terms of profitability, the new activities/businesses are small market segments that do not seem to move the generation business, since this remains a major portion of profits even in the worst-case scenario (Scenario 1). Since the generation business profits are lower in scenario 1 than in scenario 3, new activities/businesses represent a larger share of the generation business in scenario 1 than in scenario 3.

6.1.3 Conclusions

This thesis 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 thesis 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 thesis 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 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 thesis 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 2,400 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 thesis, 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 thesis 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 thesis 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 thesis is country specific, some of the findings may have similar implications in other parts of the world.

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 2kW 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 & 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 research. 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 research is country-specific, certain of the findings may have similar implications in other parts of the world.

6.2 Brazil

6.2.1 Description of the Brazilian electricity market

Several features make Brazilian power system an interesting application. Brazil is the largest power market in the Latin American region, its actual net installed capacity is 116 GW and the hydroelectric power accounts 70% of the energy produced (MME & EPE, 2015). The regulatory model in Brazil is based on long-term contracts, mechanism designed for ensuring reliable supply to consumers at least-cost expansion (Maurer & Barroso, 2011). From 2004 onwards, electricity is negotiated in two energy-trading environments: The Regulated Contracting Environment (RCE) and the Free Contracting Environment (FCE). In the RCE, distribution companies buy energy from generators through energy auctions of long-term contracts, to meet the electricity demand of captive (regulated) consumers; in the FCE, free consumers can negotiate bilateral contracts with generators (Rego, 2013). Furthermore, distribution companies are required to cover 100% of their expected demand by energy contracts.

Brazil's renewable energy target calls for 70% of its energy coming from renewable sources by 2020 (Ministry of Economic Affairs, 2015). This target attaches great importance to solar PV development in Brazil, where converge favorable conditions for solar PV such as high end-consumer electricity tariffs, low PV system costs and high-quality solar radiation – that reaches between 6.5 and 7.0 kWh/m2/day (Bueno et al., 2006). The feasibility of solar PV systems is analyzed in Brazil, particularly in Minas Gerais, the country's second largest state for rooftop solar PV potential in the residential level – 3675 MW (EPE, 2014). Although, PV adoption of the residential, industrial and commercial low voltage consumers is the focus of this study.

In 2012, Brazil introduced net-metering scheme for small-scale distributed generation systems by the regulation 482. Brazilian net-metering program enables energy producers to receive credits for providing surplus energy into the grid, which can then be used to lower next month's electricity bill or as virtual net-metering − to abate consumption costs on other locations associated to the same customer and distribution area −, this scheme allows customers that do not own roof space to take advantage of solar energy-saving opportunities (Aneel, 2012). The credits are valid for five years, and just PV systems up to 5 MW can enroll to net-metering, additionally, shortfall energy is drawn from the grid and paid at prevailing electricity tariff (Aneel, 2015).

The Brazilian Government's effort to harness the true potential of distributed solar is evidenced through other legislations such as ICMS, PIS and COFINS tax exemption for net metered solar PV systems (EPE, 2012).

Despite several studies about solar PV diffusion effects on rates, utilities and the load curve have been developed (Januzzi & Melo, 2013; Cai et al., 2013; Darghouth et al., 2016; Jiménez, Franco, & Dyner, 2016), important aspects on this topic remain unanswered, a key knowledge gap is the PV adoption among residential, small commercial and industrial customers and their feedback effect on rates and utility cost recovery. This research fills the aforementioned key gap through a system dynamic approach, which is the most proper methodology to capture the feedback structures, nonlinearities and time delays existing in the complex-problem treated in this research. Additional insights are gained of analysing the Brazilian case study, whose electricity market is characterised by long-term contracts and favourable conditions for PV market development.

The parameters used in the model correspond to the real system (see in **Table 11** the major parameters, values and sources).

Table 11. Major parameters used in the simulation model.

Parameter	Value	Units	Source
Solar capacity factor	15.5	%	(Januzzi and Melo, 2013)
PV-system size for urban households	1.2	kW	
PV-system size for rural households	2	kW	
PV-system size for industrial consumers	31.5	kW	Own calculations
PV-system size for commercial consumers	5.5	kW	
Brazil electricity demand growth	3.9	%/year	(EPE, 2014a)
Cost of the system installed residential	5900	R$/kW	
Cost of the system installed industrial	4625	R$/kW	(EPE, 2012)
Cost of the system installed commercial	5392	R$/kW	

6.2.2 Results

The modelling results show that the solar PV effects on distribution utilities in Brazil is to depressed the energy sales. Between 2016 to 2036, energy consumption from the grid decreases at rate of **2%** per year. By 2036, energy consumption from solar PV panels represents **79%** of the energy consumption from grid (See **Figure 50**).

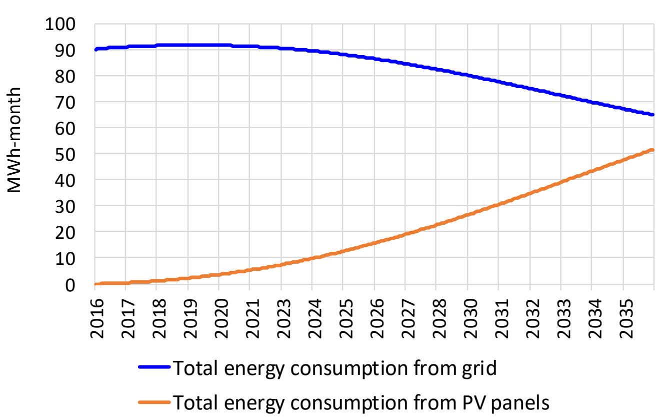

Figure 50. Total energy consumption from grid vs energy consumption from PV panels

In **Figure 51** total energy consumption from grid is calculated as the sum of residential, industrial and commercial energy consumption. From 2016 to 2036, residential energy consumption decreases at rate of **0.5%** per year, while industrial and commercial energy consumption declines at a rate of **4%** per year.

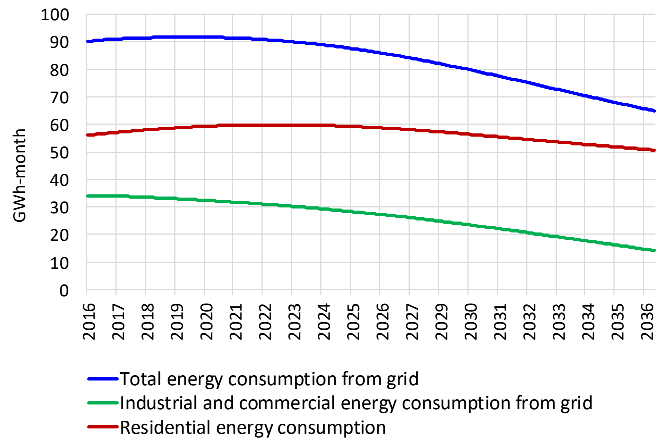

Figure 51. Energy consumption by sector

The installed PV capacity by sector is shown in **Figure 52**, by 2036, residential solar PV capacity accounts for around 59% of total installed capacity. By 2036, the percentage of PV adoption respect to the total number customers is 30% and 60% for the residential and the "industrial and commercial sector", respectively.

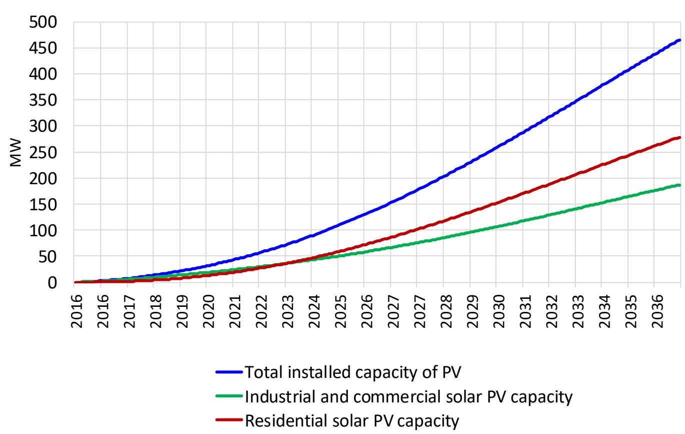

Figure 52. PV installed capacity by sector

Figure 53 depicts the energy cost for the distribution company, i.e., the cost of buying electricity to generators through contracts. Between 2016 to 2036, energy tariff declined by 11% due to solar PV penetration and contract expiration.

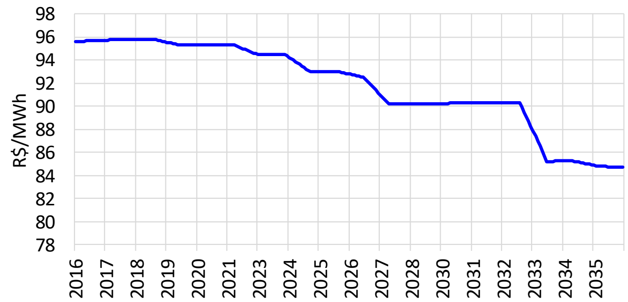

Figure 53. Energy cost for the distribution company

Between 2016 to 2036, distribution tariff for industrial and commercial customers grows by 56% (see **Figure 54Figure *54***). Similar behaviour is experienced for the distribution tariff of residential customer; between 2016 to 2036, distribution tariff for residential customers rises 55% (see **Figure 55**). Distribution tariff is calculated yearly –after a delay of 4 years– and remains constant during each period until the new tariff review, which explains the step pattern.

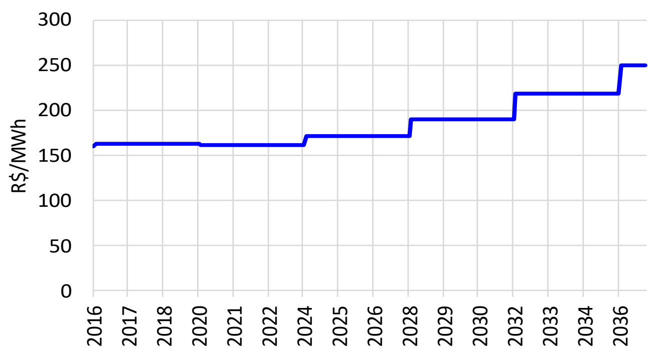

Figure 54. Distribution tariff for industrial and commercial customers

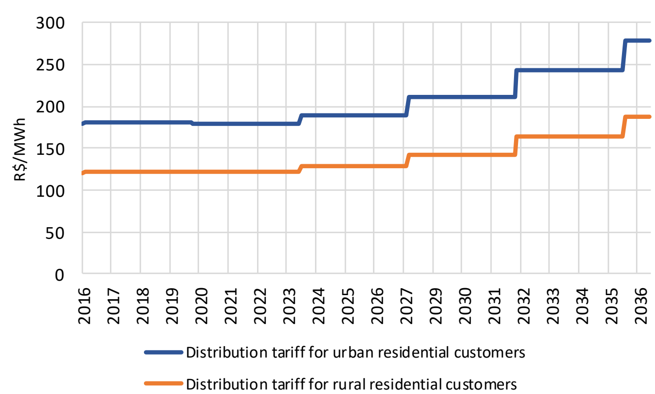

Figure 55. Distribution tariff for residential customers

Total incomes of utility experience a slightly downward trend due to energy cost reduction, while income from distribution activity presents a growing trend due to tariff revision each 4 years and losses during these periods due to PV penetration (See **Figure 56** and **Figure** *57*).

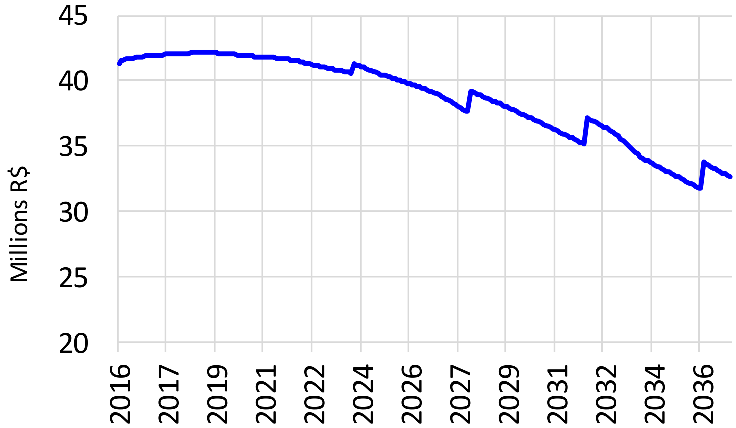

Figure 56. Total incomes of utility

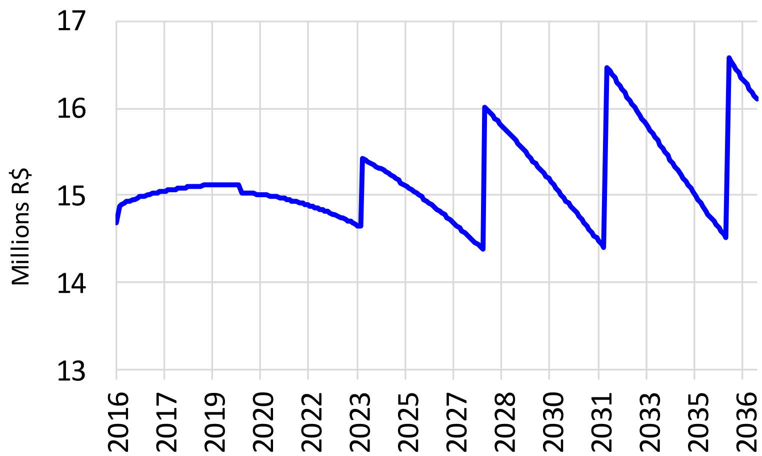

Figure 57. Incomes of utility from distribution activity

6.2.3 Conclusions

This research explores the solar PV effects on distribution utilities in Brazil. Long-term consequences of the solar PV deployment are sales depression as the result of greater PV adoption, and greater revenue losses for utilities.

Distribution tariff review exacerbates death spiral effect, making distribution tariffs higher as a consequence of PV adoption and therefore lower energy consumption.

Residential sector has the highest PV adoption, though reduction in energy consumption is low because low adoption rates.

As distribution company has energy contracts with a very long duration, energy cost is not very sensitive to high PV adoption, therefore energy cost reduction does not compensate distribution tariff increase leading to the rise of electricity tariff.

A behavior sensitivity test to confirm the high sensitivity of critical variables such as: cost of solar PV, end-consumer tariff, size of PV system, and solar radiation is necessary. It is also necessary to set different scenarios of PV penetration; each one must be correctly justified and compared with the levels of PV adoption in other parts of the world.

6.3 United Kingdom (UK)

6.3.1 Description of the UK electricity market

In the late 1980s, United Kingdom pioneered the liberalisation of electricity markets in the industrialised world. The most important changes included the creation of a wholesale electricity market – based on an electricity pool and long-term contracts– and the separation of activities along the supply chain in order to promote a competitive generation industry (Green, 2006; Newbery, 2006). Later, in 2001 the electricity pool was abolished an replaced by the New Electricity Trading Arrangements (NETA), which, in turn changed to the British Electricity Trading and Transmission Arrangements (BETTA), which incorporated Scotland into the England and Wales market (Green, 2010).

During the past few years, the political trend in the British electricity markets has not only been directed at inducing a competitive electricity industry; in 2011, British government proposed the Electricity Market Reform (EMR) seeking to reach environmental targets and delivering secure, sustainable and affordable electricity (D. Newbery, 2011). Thus, British electricity market is not only pioneer in liberalization but also in market reform for decarbonisation (Keay et al., 2013).

The environmental target for the British electricity market is to achieve 15 percent of its energy consumption from renewable sources by 2020. In addition, the UK 2020 target is to reduce Green House Gases (GHGs) by 35%, while the target in 2050 is to reduce 80 percent of Green House Gases (GHGs) (Dusonchet & Telaretti, 2015).

In 2016, the incentives to PV market were Renewable Obligation (RO) and Feed-in tariff scheme. The Feed-in tariff scheme available to small power generators was in place from 1st april 2010, PV systems lower than 50kW are only eligible for Feed-in tariff scheme (Dusonchet & Telaretti 2016). Through a contract period of 25 years, the owners of solar panel benefit from Feed-in tariff scheme as shown (Muhammad-sukki et al., 2013; Cherrington et al., 2013): (i) PV producers gain a generation tariff per kWh produced also known as FIT during a period of 20 to 25 years − a PV system for a domestic household may produce 4448 kWh-year which are paid at a FIT of 14.9p/kWh, thus a household would receive £663; (ii) the electricity exported into the grid is paid at export tariff per kWh, which is an additional payment to the FIT, it is assumed that 50% of the solar energy production is exported into the grid – the 50% of the PV energy produced is 2224kWh which are paid at the export tariff of 4.64p/kWh, thus the household would receive £103 by the exported energy; (iii) the electricity generated can be used to compensate the consumption reducing the energy bills, as 50% of the energy is exported and the remain is used to satisfy domestic energy needs the energy bill savings are equivalent to multiply 2224 kWh per the electricity of 15p/kWh resulting in £334 (See **Figure 58**).

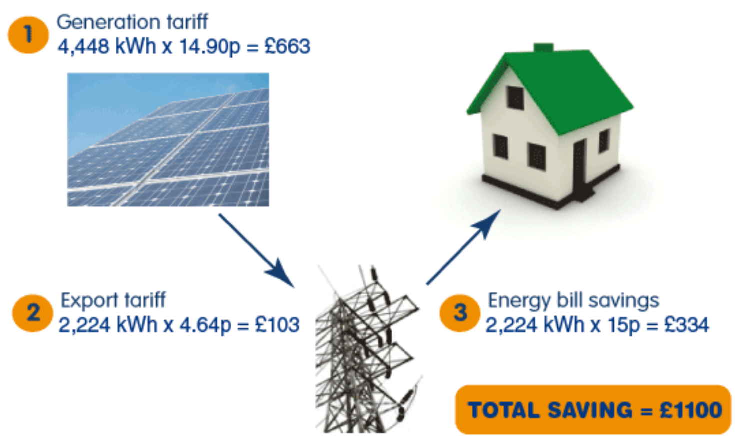

Figure 58. Feed- in tariff scheme in the British electricity market.

Source: chichestersolar.co.uk

Feed-in tariff payments are received after a process of accreditation, for PV installations lower than 50kW the PV owners and FIT supplier stablished an agreement about the feed-in tariff terms before tariff payment begin; also Feed-in tariff are affected by a digression factor that is set according to a “corridor” and PV growth, finally PV installations may receive three different feed-in tariff rates: Higher rate (H), Middle rate (M) and Lower rate (L) according to efficiency parameters (Dusonchet & Telaretti, 2015).

The incentives provided for solar PV have contributed to a significant development of solar PV systems in the British electricity market (See **Figure 59**). Recent changes in regulations have prompted uncertainty with respect to the development of solar business models however, and (tariff reductions of 64%) (See **Table 12**) many questions arise about the future and the power transition because grid parity for solar PV is near (Ofgem, 2017).

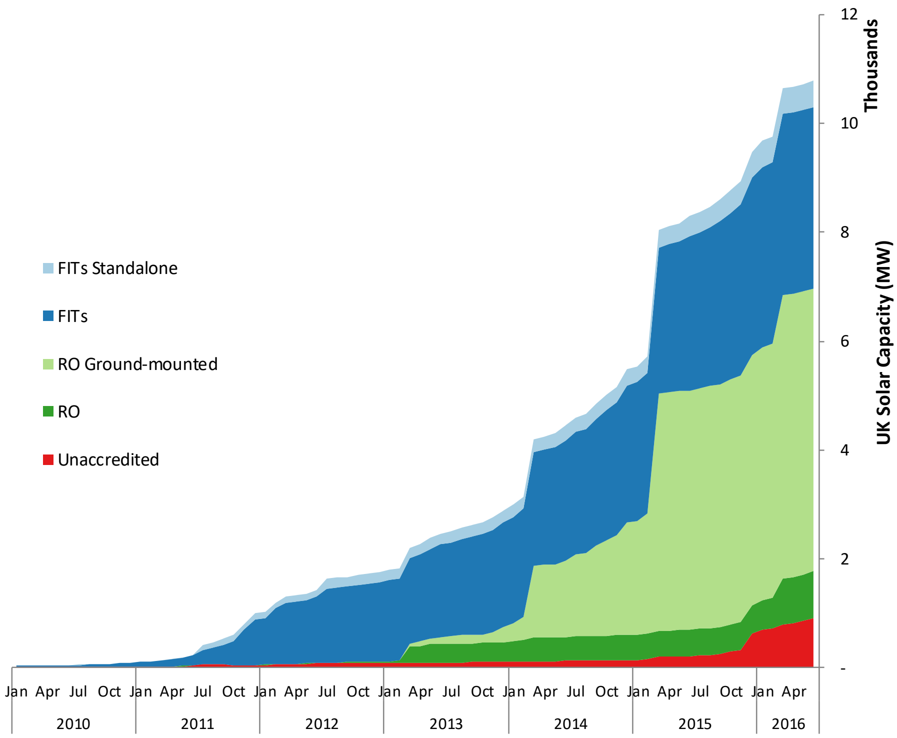

Figure 59. Cumulative installation of FIT projects in GB, categorised by incentives.

Source: Decc (2016)

Table 12. FIT tariff rates.

Tariffs (p/kWh)	Tariff January 2016 (<4kW)	Tariff February to March 2016 (<10kW)	Reduction January to February 2016 (%)
Higher rate	12.03	4.39	64%
Middle rate	10.83	3.95	64%

Lower rate	5.73	0.87	85%

Source: Ofgem (2016a).

The solar resource is a key variable for reaching the grid parity in Great Britain, where the seasonal component is significant as seen **Figure 60**.

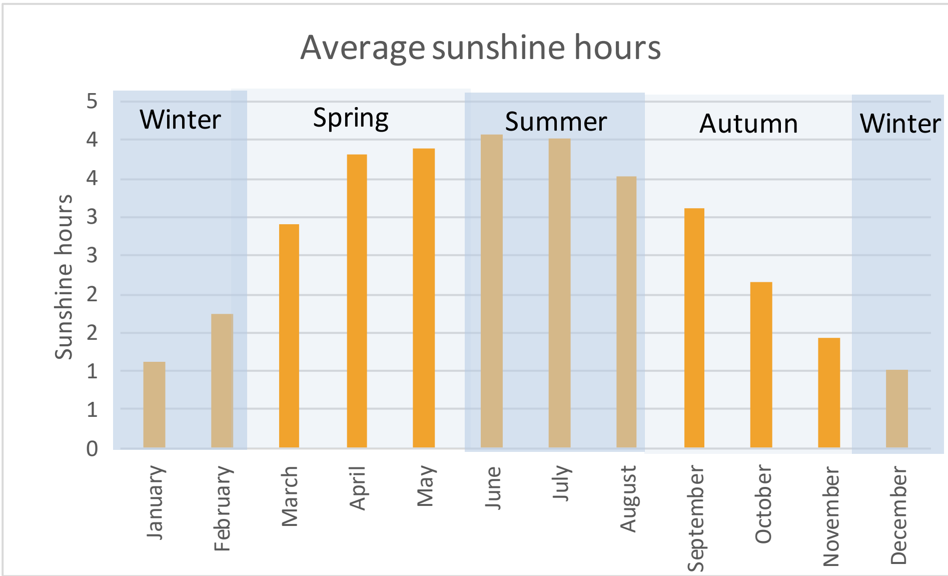

Figure 60. Solar resource in Great Britain.

Source: European Commission (2016)

Regarding to the distribution charging methodology, Ofgem sets the allowed revenue for Distributor Network Operator (DNO) , while DNOs determine the tariffs and connection charges for Ofgem approval (European Commission, 2015). The methodology used to define the allowed revenue is RIIO, which incorporates allowance for incentives, innovation and outputs; within this approach revenues are set every 8 years (European Commission, 2015). For domestic customers the methodology to determine the structure of distribution tariffs is CDCM (Common Distribution Charging Methodology), it is a long run incremental cost methodology, where the tariff is determined to recover the incremental cost associated to 500MW more of demand (T. Brown & Faruqui, 2014). Under this methodology, low voltage customer including domestic customers pay two charges: (i) a fixed or standing charge to recover the forward looking cost of low voltage networks and (ii) the volumetric charge to recover the costs of higher voltage networks (T. Brown & Faruqui, 2014).

6.3.2 Results

Feed-in tariff rates are influent on PV diffusion even after reaching PV grid parity (See **Figure 61**). When feed-in tariff rates increase then PV adoption also increases, similarly if feed-in tariff rates decreases PV adoption is also reduced. The lowest level of feed-in tariff rates leads to the lowest level of solar installed capacity. PV growth produces a reduction in energy consumption, higher rates of PV adoption lead to higher reduction of energy consumption (See **Figure 62**). However, tariff increases are minimal and therefore revenue from companies is not reduced significantly.

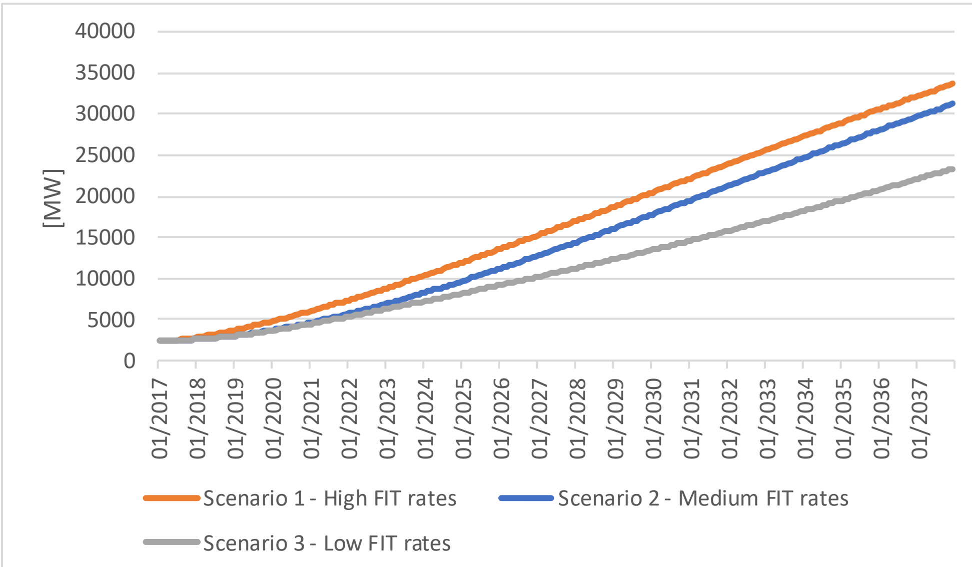

Figure 61. PV cumulative installed capacity.

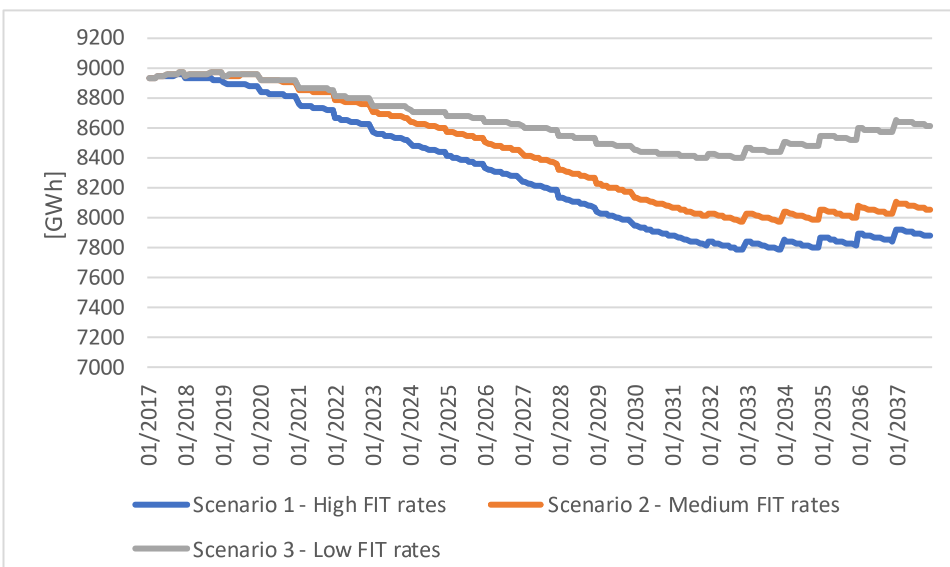

Figure 62. Monthly residential electricity demand under different feed-in tariff levels.

With lower feed-in tariff rates more customers decide to maximize their self-consumption and therefore to adopt solar PV plus battery systems (See **Figure 63)**, however as additional investment in battery storage is expensive there is a relatively slow growth of PV compared with the scenario with high feed-in tariff rates.

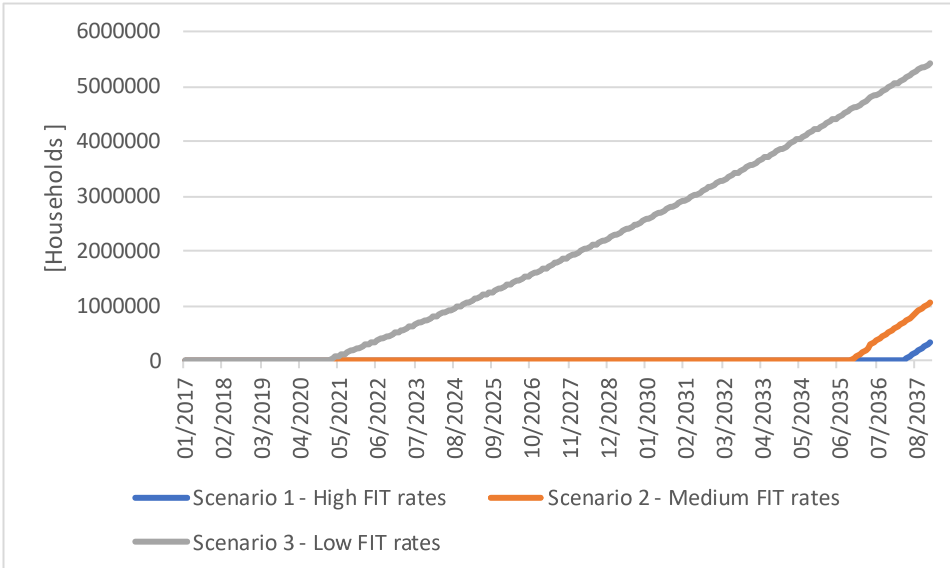

Figure 63. Households with PV system plus storage under different feed-in tariff levels.

Feed-in tariff cuts may trigger solar plus battery storage. However, the effect of batteries on revenue of electricity distribution companies seems limited due to the extra cost of batteries that should afford customers. Notwithstanding, if battery cost drops enough in the future energy consumption may be important endangering electricity distribution companies. In addition, a net metering converts the grid in a battery, since excess generation can be fed into the grid and used to offset own consumption later. In the short-term, the implementation of a net-metering may be more threatening that battery storage.

Residential rooftop solar decreases energy sales, therefore it has the potential to erode utility revenue. The impact of solar DG on utility revenue depends on the growth rate of solar PV, for example slow PV growth may lead to small increment in rates enabling full-cost recovery of utilities, however the direct consequence of solar DG continues to be the reduction of energy consumption. Here, we analyse two alternatives to address this consequence: (i) solar companies selling PV panels plus battery storage, and (ii) electric vehicles.

Solar companies are very sensitive to feed-in tariff rates since their income depends directly of them (see **Figure 64**). Feed-in tariff cuts reduces the benefit from solar companies significantly. It may suggest the need to explore different business model based on saving or efficiency instead of revenue for PV energy production. In any case the solar companies remain profitable.

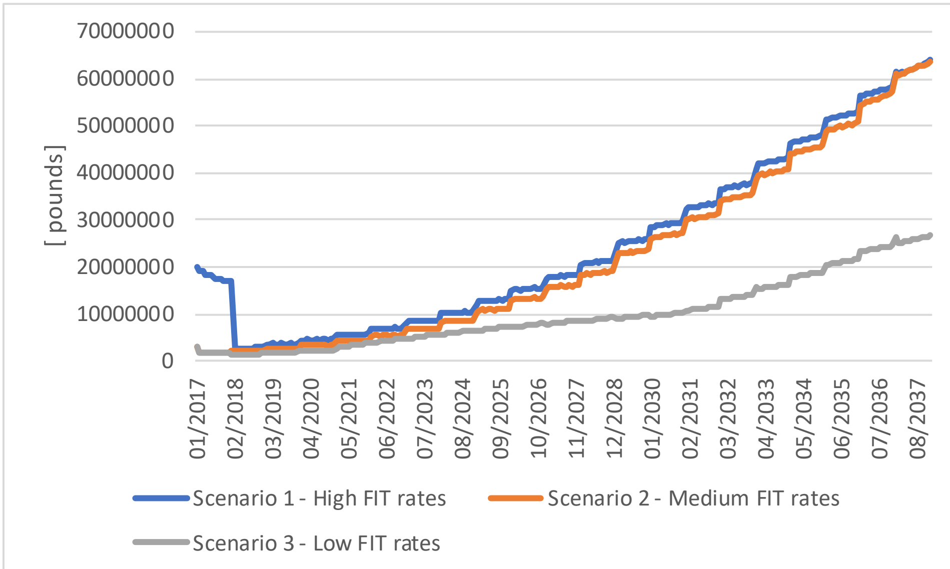

Figure 64. Benefits of solar companies under different feed-in tariff levels.

Reductions in cost of battery storage make more likely the possibility of utilities to participate in the emergent electric vehicle market. There is an opportunity to offset the declining energy consumption caused by rooftop solar, indeed, electric vehicles increase electricity sales without incurring additional cost in infrastructure (See **Figure 65**). The risk of tariff increases tied to PV growth would be mitigated because network cost would be spread over higher energy consumption, tariffs could be lowered.

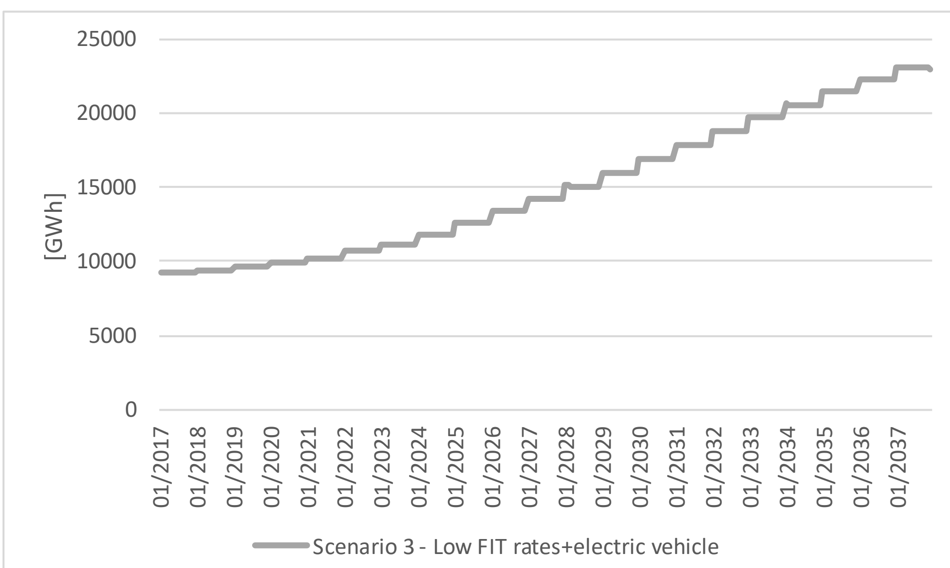

Figure 65. Energy consumption from residential sector (including electric vehicles) under a scenario of low feed-in tariff rates.

6.3.3 Conclusions

This thesis provides a holistic view of the development of distributed solar generation on traditional business models and new business models. A catastrophic scenario of the death spiral is not possible under current conditions in the British electricity market. A meaningful portion of the population may adopt solar PV systems, which will reduce the long-term income for distribution companies. On the other hand, the deployment of distributed energy resources must be seen as a whole, for instance the development of electric vehicles may increase the energy demand from the grid. Therefore, a traditional utility not necessarily will be harmed because of the power transformation.

Without subsidies, the solar PV industry will not reach high levels of development. A battery may improve the benefits for PV customers, but utilities will experience a reduction in incomes since a battery entails higher costs.

Part IV. Closure

Chapter 7. Conclusions and future work

In this final chapter, the main findings in the thesis are drawn and future research directions are identified.

In this thesis, an analysis of the impact of renewable investments on the power market was carried out. The impacts were understood from a systemic approach through identifying the positive and negative feedbacks and delays involved. Results obtained are useful for utilities dedicated to the generation and distribution business, customers, regulators and innovative companies. Although, the focus was always the utility.

The general objective of this thesis was to develop a SD model for assessing electricity utilities strategies, under environmentally friendly policies. This general objective can be broken down to four more specific objectives that would together achieve the overall goal of the thesis. Next, it is explained how each specific objective was achieved.

Objective 1: Identify threats and opportunities for electricity utilities under friendly environmental policies for large-scale renewable technologies and micro-generation projects.

A literature review was carried out to identify how renewables may affect utilities. Two phenomena were identified: merit-order effect and death spiral. Merit-order effect is a reality in some power markets with high levels of renewable investment, and it was relatively easy to demonstrate by using a simulation model. However, a death spiral needs some special circumstances such as: a volumetric charge, PV grid parity and a high level of investment in distributed solar generation. However, results suggest that in the long-term death spiral may be a threat for utilities.

Additionally, some opportunities for utilities were identified in the new business models (solar companies, Escos and electric vehicles). Though, the development of these business models depends on regulatory framework and cost-competitiveness of technologies.

Specific objective 2: Develop a simulation model where different strategies for electricity utilities can be assessed.

In this thesis was assessed the impact of renewable investments on the power market by using a SD model, the modeling framework was mainly applied to Colombian power market, but other cases were explored as the Brazilian and British power market. The modeling framework that consists of several subsystems that integrates the dynamic and structural complexities of the electricity industry, such as supply-demand interactions and their effect on investment decisions. At the same time, this modelling framework is generic, modular, adaptable and transportable structure.

Specific objective 3: Assess different strategies of an electricity utility, for different scenarios of environmental policies.

Simulation results allow to identify the main opportunities and threats for utilities. Later, an offensive and proactive strategy to face renewable energies were assessed. As the main threat in the long-term is distributed solar generation, the offensive strategy applied include changing tariff design, the implementation of net billing and connection fee. Simulation results indicated that this measure slow down PV adoption which could be inconvenient for the environment.

A proactive strategy was assessed by modelling new business models (solar companies, Escos and electric vehicles). Results suggest that in the short-term Escos may be an attractive option while in the short-term electric vehicles may be more profitable.

Defensive strategy was explored by using the most extreme scenario of the utility death spiral, where each PV household installs a 3-kW solar system, seeking a robust solution. In general all the measures deters PV investment, but the scenario with a volumetric plus fixed charge (70/30) offers the greater level of PV investment along with affordability for customers and full cost recovery.

Suggestions for improving and further developing this research are proposed:

- To model PV adoption considering other aspects that may influence the investment decision, besides the LCOE PV and electricity tariff. These aspects may be salary, education level and environmental awareness.
- Grid defection is a possibility, the effects of solar communities that become autarky may be severe on revenue of utilities.
- Other business models could be developed such as community grids, because it could serve to alleviate losses of revenue of utilities.
- The effect of changes in tariff structure such as capacity charge may be interesting, though this may also entail to model change of patterns of consumption of households.

7.1 List of publications

The appended publications to this doctoral thesis are:

Journal papers

Publication I

Castaneda, M., Franco, C. J., & Dyner, I. (2015). The effects of decarbonisation policies on the electricity sector. Ieee latin america transactions, 13(5), 1407-1413.

Publication II

Franco-Cardona, C. J., Castañeda-Riascos, M., Valencia-Arias, A., & Bermúdez-Hernández, J. (2015). The energy trilemma in the policy design of the electricity market. Dyna, 82(194), 160-169.

Publication III

Castaneda, M., Franco, C. J., & Dyner, I. (2017). Evaluating the effect of technology transformation on the electricity utility industry. Renewable and Sustainable Energy Reviews, 80, 341-351.

Publication IV

Castaneda, M., Jimenez, M., Zapata, S., Franco, C. J., & Dyner, I. (2017). Myths and facts of the utility death spiral. Energy Policy.

Publication V

Zapata, S., Garces, E., Castaneda, M., Franco, C.J. & Dyner., I. (2017). Assessing security of supply in a large-based hydroelectricity system. Energy. Submitted.

Conference papers (published proceedings)

Castaneda, M., Franco, C. J., & Dyner, I. (2015). Disruptive Challenges in Renewable Electricity: threats and opportunities for utilities. 33th International System Dynamics Conference. Boston, USA. 2015.

Castaneda, M., Jimenez, M., Zapata, S., Franco, C. J., & Dyner, I. (2016). Exploring the impact of residential PV systems on electricity utilities and customers. 34th International System Dynamics Conference. Delft, Netherlands. 2016.

De Castro, N., Dantas, G., Ferreira, D., Zapata, S., Castaneda, M., Franco, C.J., Dyner, I. (2017). Simulation model to assess the long-term effects of distributed PV deployment in the distribution industry. Rio de Janeiro. 6to ELAEE.

Castaneda, M., Jimenez, M., Zapata, S., Franco, C. J., & Dyner, I. (2017). A systemic approach to assess the impact of distributed solar energy on utilities and customers: implications for energy policy. 6 ELAEE. Rio de Janeiro, Brazil.

Castaneda, M., Jimenez, M., Zapata, S., Franco, C. J., & Dyner, I. (2017). Exploring the impact of residential PV systems on electricity utilities and customers. 35th International System Dynamics Conference. Boston, USA.

Working papers

De Castro, N., Dantas, G., Ferreira, D., Zapata, S., Castaneda, M., Franco, C.J., Dyner, I. (2017). Assessing the long-term effects of PV penetration in the Brazilian distribution industry (working paper).

Castaneda, M., Zapata, S., Cherni, J., Aristizabal, A. J., Franco, C. J., & Dyner, I. (2017). 1. Solar energy: a business threat or opportunity for the power industry? (working paper).

Castaneda, M., Quiceno, G., Alvarez, C., Franco, C. J., Mejia, L.,& Dyner, I. (2017).Simulating power transformation scenarios for the utility Blue Ocean Strategy (working paper).

Table 13 illustrates the publications and chapters in which the different specific objectives are achieved.

Table 13. Compliance of objectives in the publications and chapters

Objective	Publications	Chapters
First objective	Publication I Publication II Publication III	Chapter 2
Second objective	Publication I Publication III	Chapter 5
Third objective	Publication II	Chapter 3 Chapter 6

7.2 Scientific contribution

The scientific contributions of this thesis can be summarized as follows:

- First, the state of art review that contains: (i) researches about the impacts of renewable investments on the power market, specially distributed solar PV, (ii) studies that treat the measures for regulator and utilities to face the transition toward a decentralized and cleaner power system, such as: rate design reforms, compensation schemes reforms and new business models.

- Second, this research contributes to the understanding of power market dynamics and, in particular, the feedback cycles that describe the effects of: renewable investments on the power market and policy alternatives to address the transition. This is clearly important to utilities and regulator avoid any side effect.

- Third, novel simulation model to define and quantify the long-term effects of renewable investments on the power market considering complex aspects such as delays, non-linearities and feedback loops. The simulation model is applied to Colombia, Brazil and UK electricity market. Therefore, this simulation model is flexible and tractable.

- Fourth, the better path for regulator and utilities address the transition of the power market is defined through the dynamic assessment of various policy alternatives. It is demonstrated the need of a policy intervention of regulator and an innovative strategy for utilities.

ANNEX

This annex contains summary tables of the main four publications:

Paper 1.

Castaneda, M., Franco, C. J., & Dyner, I. (2017). Evaluating the effect of technology transformation on the electricity utility industry. Renewable and Sustainable Energy Reviews, 80, 341-351.

Paper 2.

Castaneda, M., Jimenez, M., Zapata, S., Franco, C. J., & Dyner, I. (2017). Myths and facts of the utility death spiral. Energy Policy.

Paper 3.

Castaneda, M., Zapata, S., Cherni, J., Aristizabal, A. J., Franco, C. J., & Dyner, I. (2017). 1. Solar energy: a business threat or opportunity for the power industry ? (working paper).

Paper 4.

De Castro, N., Dantas, G., Ferreira, D., Zapata, S., Castaneda, M., Franco, C.J., Dyner, I. (2017). Assessing the long-term effects of PV penetration in the Brazilian distribution industry (working paper).

Assumptions according to study cases				
Variable	**Paper 1**	**Paper 2**	**Paper 3**	**Paper 4**
Country	Colombia	Colombia	United Kingdom	Brazil-Minais Gerais
Perspective	Utility “Company A” and Sector perspective	Sector perspective, utility as a whole	Sector perspective	Utility “Company A”(D, R) and Sector perspective
Compensation scheme	Net metering	Net metering	Feed-in tariff plus export tariff	Net metering
Sector of PV adoption	Residential	Residential	Residential	Residential Commercial Industrial
Electricity dispatch	Visual basic algorithm to model electricity dispatch	Electricity dispatch depends on electricity margin	Exogenous	Wp: Contracts
Capacity mechanism	Yes, capacity market	No	No	Exogenous
Batteries	No	No	Yes	No
Regulatory Lag (tariffs no immediately adjusted)	No	No	No	Yes

Table 14. Summary of assumptions from papers.

Model results			
Variable	**Utilities**	**Customers**	**Regulator**
Paper 1	Generation business may be affect it by the entrance of hydro power plants and renewable energies at large-scale. Distribution business may be affected by solar DG in the long-term. The effect may be intensified if PV households over install or if all sectors adopt solar DG	Non-PV adopters may experience high tariffs if utilities increase them to compensate energy reduction caused by solar PV	Strong environmental policy is more important to encourage renewable energies. High adoption of distributed solar generation may cause problems of affordability.
Paper 2	Strategies of utilities to face transition: a. Reactive: means to deter solar PV adoption. b. Proactive: means to adapt new business models. First strategy may work for utilities only in the short term.	Non-PV adopters may experience high tariffs if utilities increase them to compensate energy reduction caused by solar PV PV adopters may experience high benefits. Measures such as: net-metering, higher fixed costs, back-up fee may deter solar PV adoption	System collapses by death spiral when: i) Households are over-installed (or other sectors move into PV rooftop); ii) Death spiral involves a myopic utility strategy; iii) Bad regulation. It is necessary a policy that guarantees high PV adoption and full remuneration of utility.
Paper 3	Lower compensation to distributed solar generation may motivate the investment in batteries. Solar companies show a growing trend, they should not depend on incentives. Electric vehicles may compensate any lost caused by distributed solar generation.	Lower compensation to distributed solar generation may motivate the adoption of solar plus battery PV system.	Feed-in tariff cuts may reduce adoption rates but the adoption of solar plus battery PV system is also possible in the long-term. Lastly, the speed of battery PV adoption depends on learning curve of battery.
Paper 4	In the long-term, utilities with energy supply contracts may be affected by the reduction in energy consumption tied to distributed solar generation.	Customers may be benefit from regulation because lower energy costs imply lower energy bills. Residential sector has the highest PV adoption	Regulatory lag may cause oscillation in tariffs.

Table 15. Summary of results from papers.

References

Abella, A. (2015). Smart Energy : New Applications and Business Models The Boston Consulting Group in collaboration with the Energy Chair of Orkestra, (April). Available at: http://www.orkestra.deusto.es/images/investigacion/publicaciones/smart_energy_en_15072015.pdf

Abrardi, L., & Cambini, C. (2015). Tariff regulation with energy efficiency goals. *Energy Economics*, *49*, 122–131.

Ackermann, T. (2001). Distributed generation : a definition. *Electric Power Systems Research*, *57*, 195–204.

ActewAGL. (2015). Proposed Tariff Structure Statement. *Electric Power Systems Research.*

Akorede, M. F., Hizam, H., & Pouresmaeil, E. (2010). Distributed energy resources and benefits to the environment. *Renewable and Sustainable Energy Reviews*, *14*, 724–734. http://doi.org/10.1016/j.rser.2009.10.025

Aneel. (2012). *Resolução Normativa Nº 482, de 17 de Abril de 2012*. Available at: http://www2.aneel.gov.br/arquivos/PDF/Resolução Normativa 482, de 2012 - bip-junho-2012.pdf

Aneel. (2015). *Agência nacional de energia elétrica – aneel resolução normativa Agência nacional de energia elétrica – aneel resolução normativa N° 687*. Available at: https://www.portalsolar.com.br/media/files/RESOLUCAO NORMATIVA REN 687_2015.pdf

Antonelli, M., & Desideri, U. (2014). The doping effect of Italian feed-in tariffs on the PV market. *Energy Policy*, *67*, 583–594. http://doi.org/10.1016/j.enpol.2013.12.025

Asmus, P. (2008). Exploring New Models of Solar Energy Development. *The Electricity Journal*, *21*(3), 61–70.

Bacon, R. W., & Besant-Jones, J. (2001). Global Electric Power Reform, Privatization, and Liberalization of the Electric Power Industry in Developing Countries1. *Annual Review of Energy and the Environment*, *26*, 331–359. http://doi.org/10.1146/annurev.energy.26.1.331

Badham, J. (2010). A Compendium of Modelling Techniques. *Integration Insights*, (12), 24. http://doi.org/1834-304X

Bagdasaryan, A. (2011). Discrete dynamic simulation models and technique for complex control systems.

Simulation Modelling Practice and Theory, *19*(4), 1061–1087. http://doi.org/10.1016/j.simpat.2010.12.010

Ballester, C., & Furió, D. (2015). Effects of renewables on the stylized facts of electricity prices. *Renewable and Sustainable Energy Reviews*, *52*, 1596–1609. http://doi.org/10.1016/j.rser.2015.07.168

Barbose, G., Miller, J., Sigrin, B., Reiter, E., Cory, K., & Mclaren, J. (2016). *On the Path to SunShot : Utility Regulatory and Business Model Reforms for Addressing the Financial Impacts of Distributed Solar on Utilities*.

Barlas, Y. (1996). Formal aspects of model validity and validation in system dynamics. *System Dynamics Review*, *12*(3), 183–210.

Bass, F. (1969). A new product growth for model consumer durables. *Management Science*, *15*(5), 215–227.

Batlle, C. (2011). A method for allocating renewable energy source subsidies among final energy consumers. *Energy Policy*, *39*(5), 2586–2595. http://doi.org/10.1016/j.enpol.2011.02.027

Bayod-Rújula, A. a. (2009). Future development of the electricity systems with distributed generation. *Energy*, *34*(3), 377–383. http://doi.org/10.1016/j.energy.2008.12.008

Behrangrad, M. (2015). A review of demand side management business models in the electricity market. *Renewable and Sustainable Energy Reviews*, *47*, 270–283. http://doi.org/10.1016/j.rser.2015.03.033

Bierlaire, M. (1998). Discrete choice models. *Operations Research and Decision Aid Methodologies in Traffic and Transportation Management. Springer Berlin Heidelberg*, 203–227.

Böhringer, C., Löschel, A., Moslener, U., & Rutherford, T. F. (2009). EU climate policy up to 2020: An economic impact assessment. *Energy Economics*, *31*, S295–S305. http://doi.org/10.1016/j.eneco.2009.09.009

Bolton, R., & Hannon, M. (2016). Governing sustainability transitions through business model. *Research Policy*. http://doi.org/10.1016/j.respol.2016.05.003

Bonbright, J. C., Danielsen, A. L., & Kamerschen, D. R. (1961). Principles of public utility rates. *New York: Columbia University Press.*

Borshchev, A., & Filippov, A. (2004a). From System Dynamics and Discrete Event to Practical Agent Based Modeling : Reasons , Techniques , Tools 1 . Simulation Modeling : Abstraction Levels , Major

Paradigms. *22nd International Conference of the System Dynamics Society, 25-29 July 2004*, 45. Retrieved from http://web.ics.purdue.edu/~hwan/IE680/Final Presentation/Po-CHing/From SD and DE to Practical Agent Based Modeling Reasons Techniques Tools 04.pdf

Borshchev, A., & Filippov, A. (2004b). From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools. *The 22nd International Conference of the System Dynamics Society*.

Brennan, T. J. (2013). Energy Efficiency Policy : Surveying the Puzzles. *The Energy Journal*, *34*(2).

Breyer, C., & Gerlach, A. (2013). Global overview on grid parity. *Progress in Photovoltaics: Research and Applications*, *21*(1), 121–136.

Bronski, Peter; Creyts, Jon; Guccione, Leia; Madrazo, Maite;Mandel, J., Rader, B., & Seif, Dan; Liliental, Peter; Glassmire, John; Abromowitz, Jeffrey; Crowdis, Mark; Richardson, John; Schmidt, E. T. H. (2014). *The economics of grid defection: When and where distributed solar generation plus storage competes with traditional utility service*. Retrieved from http://www.rmi.org/electricity_grid_defection#economics_of_grid_defection

Brouwer, A. S., van den Broek, M., Seebregts, A., & Faaij, A. (2014). Impacts of large-scale Intermittent Renewable Energy Sources on electricity systems, and how these can be modeled. *Renewable and Sustainable Energy Reviews*, *33*, 443–466. http://doi.org/10.1016/j.rser.2014.01.076

Brown, A., & Lund, L. (2013). Distributed Generation: How Green? How Efficient? How Well-Priced? *The Electricity Journal*, *26*(3), 28–34. http://doi.org/10.1016/j.tej.2013.02.016

Brown, T., & Faruqui, A. (2014). Structure of Electricity Distribution Network Tariffs : Recovery of Residual Costs. *Australian Energy Market Commission*, (August).

Bueno Pereira, E., Ramos Martins, F., Luna de Abreu, S., & Rüther, R. (2006). *Brazilian Atlas of solar energy*.

Cai, D. W. H., Adlakha, S., Low, S. H., Martini, P. De, & Chandy, K. M. (2013). Impact of residential PV adoption on Retail Electricity Rates. *Energy Policy*, *62*, 830–843. http://doi.org/10.1016/j.enpol.2013.07.009

Castaneda, M., Franco, C., & Dyner, I. (2016). The effect of technology transformation on the electricity utility industry.

Castaneda, M., Franco, C. J., & Dyner, I. (2017). Evaluating the effect of technology transformation on the electricity utility industry. *Renewable and Sustainable Energy Reviews*, *80*(65), 341–351. http://doi.org/10.1016/j.rser.2017.05.179

Castaneda, M., Jimenez, M., Zapata, S., Franco, C. J., & Dyner, I. (2017). *Myths and facts of the utility death spiral*.

Cepeda, M., & Finon, D. (2013). How to correct for long-term externalities of large-scale wind power development by a capacity mechanism? *Energy Policy*, *61*, 671–685. http://doi.org/10.1016/j.enpol.2013.06.046

Chappin, É. J. L. (2011). *Simulating Energy Transitions 42*. TU Delft, Delft University of Technology.

Cherrington, R., Goodship, V., Long, A., & Kirwan, K. (2013). The feed-in tariff in the UK : A case study focus on domestic photovoltaic systems, *50*, 2–7. http://doi.org/10.1016/j.renene.2012.06.055

Christensen, C. M. (1997). *The Innovator's Dilemma: when new technologies cause great firms to fail*. Boston: Harvard Business School Press. Retrieved from http://www.amazon.ca/exec/obidos/redirect?tag=citeulike09-20&path=ASIN/0060521996

Ciarreta, A., Espinosa, M. P., & Pizarro-Irizar, C. (2014). Is green energy expensive? Empirical evidence from the Spanish electricity market. *Energy Policy*, *69*, 205–215. http://doi.org/10.1016/j.enpol.2014.02.025

Clò, S., Cataldi, A., & Zoppoli, P. (2015). The merit-order effect in the Italian power market: The impact of solar and wind generation on national wholesale electricity prices. *Energy Policy*, *77*, 79–88. http://doi.org/http://dx.doi.org/10.1016/j.enpol.2014.11.038

Cludius, J., & Hermann, H. (2013). The Merit Order Effect of Wind and Photovoltaic Electricity Generation in Germany 2008-2012 by. *Centre for Energy and Environmental Markets (CEEM), Working Pa*(May), 1–28.

Congreso de la República de Colombia. Ley 1715. Por la cual se regula la integración de las energías renovables no convencionales al Sistema Energético Nacional (2014). Colombia.

Costello, K. W. (2015). Major Challenges of Distributed Generation for State Utility Regulators. *The Electricity Journal*, *28*(3), 8–25. http://doi.org/10.1016/j.tej.2015.03.002

Costello, K. W., & Hemphill, R. C. (2014). Electric Utilities' "Death Spiral": Hyperbole or Reality? *The Electricity Journal*, *27*(10), 7–26. http://doi.org/10.1016/j.tej.2014.09.011

Coughlin, J., Grove, J., Irvine, L., Janet, F., Phillips, S. J., & Moynihan, L. (2011). A Guide to Community Solar: Utility,Private and Non-Profit Project Development.

Couture, T., & Gagnon, Y. (2010). An analysis of feed-in tariff remuneration models: Implications for renewable energy investment. *Energy Policy*, *38*(2), 955–965. http://doi.org/10.1016/j.enpol.2009.10.047

Cowart, R. (2011). Prices and Policies : Carbon Caps and Efficiency Programmes for Europe ' s Low - Carbon Future. In *Proceedings of the ECEEE Summer Study 2011*.

CREG. Resolución 31 de 1997 - Formula tarifaria (1997). Colombia. Retrieved from http://apolo.creg.gov.co/Publicac.nsf/1c09d18d2d5ffb5b05256eee00709c02/33253893deaeed5f0525785a007a5ec3/$FILE/Crg31-97.pdf

DANE. (2015). Estimaciones y proyección de población; estimaciones y proyecciónes de hogares y viviendas. Retrieved November 3, 2015, from http://www.dane.gov.co/index.php/poblacion-y-demografia/proyecciones-de-poblacion

Darghouth, N. R., Barbose, G., & Wiser, R. (2011). The impact of rate design and net metering on the bill savings from distributed PV for residential customers in California. *Energy Policy*, *39*, 5243–5253. http://doi.org/10.1016/j.enpol.2011.05.040

Darghouth, N. R., Wiser, R. H., Barbose, G., & Mills, A. D. (2016). Net metering and market feedback loops : Exploring the impact of retail rate design on distributed PV deployment, *162*, 713–722. http://doi.org/10.1016/j.apenergy.2015.10.120

Day, C., & Bunn, D. (2001). Divestiture of generation assets in the electricity pool of England and wales: a computational approach to analyzing market power. *Journal of Regulatory Economics*, *19*(2), 123–141.

De Jonghe, C., Delarue, E., Belmans, R., & D'haeseleer, W. (2009). Interactions between measures for the support of electricity from renewable energy sources and CO2 mitigation. *Energy Policy*, *37*(11), 4743–4752. http://doi.org/10.1016/j.enpol.2009.06.033

Del Río, P. (2009). Interactions between climate and energy policies: the case of Spain. *Climate Policy*, *9*(2), 119–138. http://doi.org/10.3763/cpol.2007.0424

del Río, P. (2010). Analysing the interactions between renewable energy promotion and energy efficiency support schemes: The impact of different instruments and design elements. *Energy Policy*, *38*(9), 4978–4989. http://doi.org/10.1016/j.enpol.2010.04.003

del Río, P. (2012). The dynamic efficiency of feed-in tariffs: The impact of different design elements. *Energy Policy*, *41*, 139–151. http://doi.org/10.1016/j.enpol.2011.08.029

Del Río, P., & Mir-Artigues, P. (2012). Support for solar PV deployment in Spain: Some policy lessons. *Renewable and Sustainable Energy Reviews*, *16*, 5557–5566. http://doi.org/10.1016/j.rser.2012.05.011

Delarue, E., & D'haeseleer, W. (2008). Greenhouse gas emission reduction by means of fuel switching in electricity generation: Addressing the potentials. *Energy Conversion and Management*, *49*(4), 843–853. http://doi.org/10.1016/j.enconman.2007.06.026

Deloitte. (2015). *The future of the global power sector*. Retrieved from https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Energy-and-Resources/gx-power-future-global-power-sector-report.pdf

Dillig, M., Jung, M., & Karl, J. (2016). The impact of renewables on electricity prices in Germany – An estimation based on historic spot prices in the years 2011 – 2013. *Renewable and Sustainable Energy Reviews*, *57*, 7–15. http://doi.org/10.1016/j.rser.2015.12.003

Drury, E., Miller, M., Macal, C. M., Graziano, D. J., Heimiller, D., Ozik, J., & Perry, T. D. (2012). The transformation of southern California ' s residential photovoltaics market through third-party ownership. *Energy Policy*, *42*, 681–690. http://doi.org/10.1016/j.enpol.2011.12.047

Dufo-López, R., & Bernal-Agustín, J. L. (2015). A comparative assessment of net metering and net billing policies. Study cases for Spain. *Energy*, *84*, 684–694. http://doi.org/10.1016/j.energy.2015.03.031

Dusonchet, L., & Telaretti, E. (2015). Comparative economic analysis of support policies for solar PV in the most representative EU countries. *Renewable and Sustainable Energy Reviews*, *42*, 986–998. http://doi.org/10.1016/j.rser.2014.10.054

Dyner, I. (2000). Energy modelling platforms for policy and strategy support. *Journal of the Operational Research Society*, *51*(2), 136–144. http://doi.org/10.2307/254253

Dyner, I., & Franco, C. J. (2004). Consumers' bounded rationality: The case of competitive energy markets. *Systems Research and Behavioral Science*, *21*, 373–389. http://doi.org/10.1002/sres.644

Dyner, I., & Larsen, E. R. (2001). From planning to strategy in the electricity industry. *Energy Policy*, *29*(13), 1145–1154. http://doi.org/10.1016/S0301-4215(01)00040-4

EC. (2008). *European Commission. The support of electricity from renewable energy sources*.

EECA. (2010). *Domestic-scale distributed generation Guidance for local government*.

Eid, C., Reneses, J., Frías, P., & Hakvoort, R. (2014). The economic effect of electricity net-metering with solar PV : Consequences for network cost recovery , cross subsidies and policy objectives. *Energy Policy*, *75*, 244–254. http://doi.org/10.1016/j.enpol.2014.09.011

El-Khattam, W., & Salama, M. M. a. (2004). Distributed generation technologies, definitions and benefits. *Electric Power Systems Research*, *71*(August 2002), 119–128. http://doi.org/10.1016/j.epsr.2004.01.006

Engelken, M., Römer, B., Drescher, M., Welpe, I. M., & Picot, A. (2016). Comparing drivers , barriers , and opportunities of business models for renewable energies : A review. *Renewable and Sustainable Energy Reviews*, *60*, 795–809. http://doi.org/10.1016/j.rser.2015.12.163

EON. (2014). Our new strategy: “Empowering customers. Shaping markets.” Retrieved October 10, 2016, from http://www.eon.com/en/about-us/strategy/strategy.html

EPE. (2012). Análise da Inserção da Geração Solar na Matriz Elétrica Brasileira.

EPE. (2014). *Inserção da Geração Fotovoltaica Distribuída no Brasil – Condicionantes e Impactos*.

EPIA. (2014). *GLOBAL MARKET OUTLOOK for photovoltaics 2014 -2018*. Retrieved from www.epia.org

EPRI. (2014). *The Integrated Grid: Realizing the Full Value of Central and Distributed Energy Resources*. California. Retrieved from http://tdworld.com/site-files/tdworld.com/files/uploads/2014/02/integratedgridepri.pdf

Eurelectric. (2013). Network tariff structure for a smart energy system, (May).

European Commission. (2015). *Study on tariff design for distribution systems*.

European Commission. (2016). Photovoltaic Geographical Information System. Joint research centre. Institute for energy and transport. Retrieved November 3, 2016, from http://re.jrc.ec.europa.eu/pvgis/solres/solres.htm

Faruqui, A., & Hledik, R. (2015). An Evaluation of SRP ' s Electric Rate Proposal for Residential Customers with Distributed Generation.

Felder, F. a., & Athawale, R. (2014). The life and death of the utility death spiral. *Electricity Journal*, *27*(6), 9–16. http://doi.org/10.1016/j.tej.2014.06.008

Firestone, R., Marnay, C., & Maribu, K. M. (2006). The Value of Distributed Generation under Different Tariff Structures. *2006 ACEEE Summer Study on Energy Efficiency in Buildings*, (May), 15.

Ford, A. (1997). System Dynamics and the Electric Power Industry. *System Dynamics Review*, *13*(1), 57–85. http://doi.org/10.1002/(SICI)1099-1727(199721)13:1<57::AID-SDR117>3.0.CO;2-B

Ford, A. (1999). Cycles in competitive electricity markets: a simulation study of the western United States. *Energy Policy*, *27*(11), 637–658. http://doi.org/10.1016/S0301-4215(99)00050-6

Ford, A. (2001). Waiting for the boom : a simulation study of power plant construction in California, *29*, 847–869.

Ford, A. (2002). Boom and Bust in Power Plant Construction : Lessons from the California Electricity Crisis. *Journal of Industry, Competition and Trade*, *2*(1-2), 59–74.

Forrester, J. W., & Senge, P. M. (1996). Tests for building confidence in system dynamics models. Modelling for management: simulation in support of systems thinking, 414–434.

Franco, C. J., Castaneda, M., & Dyner, I. (2015). Simulating the new British Electricity-Market Reform. *European Journal of Operational Research*, *245*(1), 273–285. http://doi.org/10.1016/j.ejor.2015.02.040

Frantzis, L., Graham, S., Katofsky, R., & Sawyer, H. (2008). Photovoltaics Business Models. *Renewable Energy*, (February).

Frías, P., Gómez, T., Cossent, R., & Rivier, J. (2009). Improvements in current European network regulation to facilitate the integration of distributed generation. *International Journal of Electrical Power and Energy Systems*, *31*(9), 445–451. http://doi.org/10.1016/j.ijepes.2009.03.001

Funkhouser, E., Blackburn, G., Magee, C., & Rai, V. (2015). Business model innovations for deploying distributed generation : The emerging landscape of community solar in the U.S. *Energy Research & Social Science*, *10*, 90–101. http://doi.org/10.1016/j.erss.2015.07.004

Garcez, C. A. G. (2017). What do we know about the study of distributed generation policies and regulations in the Americas ? A systematic review of literature. *Renewable and Sustainable Energy Reviews*, *75*(August 2015), 1404–1416. http://doi.org/10.1016/j.rser.2016.11.129

Gianelloni, F., De Azevedo Dantas, G., Alves, J. F., & De Castro, N. (2017). The distributed electricity generation diffusion impact on the Brazilian distribution utilities.

Gischler, C., & Janson, N. (2011). *Perspectives for Distributed Generation with Renewable Energy in Latin America and the Caribbean*.

Grace, W. (2015). Exploring the Death Spiral : A system dynamics model of the electricity network in Western Australia.

Green, J., & Newman, P. (2017). Citizen utilities : The emerging power paradigm. *Energy Policy*, *105*(February), 283–293. http://doi.org/10.1016/j.enpol.2017.02.004

Green, R. (2006). Market power mitigation in the UK power market. *Utilities Policy*, *14*, 76–89. http://doi.org/10.1016/j.jup.2005.09.001

Green, R. (2010). Are the British electricity trading and transmission arrangements future-proof. *Utilities Policy*, *18*(4), 186–194.

Grübler, A. (2010). *Technological change and the environment*. *Routledge*. Routledge.

GWEC. (2017). *Global wind statistics 2016*. Retrieved from http://www.gwec.net/wp-content/uploads/vip/GWEC_PRstats2016_EN_WEB.pdf

Haas, R., Lettner, G., Auer, H., & Duic, N. (2013). The looming revolution: How photovoltaics will change electricity markets in Europe fundamentally. *Energy*, *57*, 38–43. http://doi.org/10.1016/j.energy.2013.04.034

Haas, R., Panzer, C., Resch, G., Ragwitz, M., Reece, G., & Held, A. (2011). A historical review of promotion strategies for electricity from renewable energy sources in EU countries. *Renewable and Sustainable Energy Reviews*, *15*(2), 1003–1034. http://doi.org/10.1016/j.rser.2010.11.015

Hamwi, M., & Lizarralde, I. (2017). A review of business models towards service-oriented electricity systems. *Procedia CIRP*, *64*, 109–114. http://doi.org/10.1016/j.procir.2017.03.032

Heinberg, R., & Fridley, D. (2016). *Our renewable future: laying the path for one hundred percent clean energy*. (Island Pre).

Helms, T., Loock, M., & Bohnsack, R. (2016). Timing-based business models for fl exibility creation in the electric power sector. *Energy Policy*, *92*, 348–358. http://doi.org/10.1016/j.enpol.2016.02.036

Hindsberger, M., Nybroe, M. H., Ravn, H. F., & Schmidt, R. (2003). Co-existence of electricity, TEP, and TGC markets in the Baltic Sea Region. *Energy Policy*, *31*(1), 85–96. http://doi.org/10.1016/S0301-4215(02)00120-9

Hledik, R. (2014). Rediscovering Residential Demand Charges. *The Electricity Journal*, *27*(7), 82–96. http://doi.org/10.1016/j.tej.2014.07.003

Http://connect.xcelenergy.com. (2017). Understanding Decoupling: Saving More by Using Less. Retrieved from http://connect.xcelenergy.com/understanding-decoupling-saving-more-by-using-less/

Huijben, J. C. C. M., & Verbong, G. P. J. (2013). Breakthrough without subsidies ? PV business model experiments in the Netherlands. *Energy Policy*, *56*(January 2012), 362–370. http://doi.org/10.1016/j.enpol.2012.12.073

Huijben, J. C. C. M., Verbong, G. P. J., & Podoynitsyna, K. S. (2015). Mainstreaming solar : Stretching the regulatory regime through business model innovation. *Environmental Innovation and Societal Transitions*. http://doi.org/10.1016/j.eist.2015.12.002

Ibanez-lopez, A. S., Martinez-val, J. M., & Moratilla-soria, B. Y. (2017). A dynamic simulation model for assessing the overall impact of incentive policies on power system reliability , costs and environment. *Energy Policy*, *102*(October 2016), 170–188. http://doi.org/10.1016/j.enpol.2016.12.026

IEA. (2015). *Medium-Term Renewable Energy Market Report 2015*.

IEA. (2016). *Chapter 5. Electricity*. *International energy outlook*. Washington, DC. Retrieved from https://www.eia.gov/outlooks/ieo/electricity.php

IPCC. (2011). *RENEWABLE ENERGY SOURCES AND CLIMATE CHANGE MITIGATION SUMMARY FOR POLICYMAKERS AND TECHNICAL SUMMARY*. Retrieved from https://www.ipcc.ch/pdf/special-reports/srren/SRREN_FD_SPM_final.pdf

Irena. (2015). *Renewable Energy Target Setting*. Retrieved from http://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Target_Setting_2015.pdf

Irena. (2016). *The power to change: solar and wind cost reduction potential to 2025*. Retrieved from http://www.irena.org/DocumentDownloads/Publications/IRENA_Power_to_Change_2016.pdf

Irena. (2017). *Rethinking energy accelerating the global energy transformation*. Retrieved from http://www.irena.org/DocumentDownloads/Publications/IRENA_REthinking_Energy_2017.pdf

Januzzi, G. D. M., & Melo, C. A. de. (2013). Energy for Sustainable Development Grid-connected photovoltaic in Brazil : Policies and potential impacts for 2030. *Energy for Sustainable Development*, *17*(1), 40–46. http://doi.org/10.1016/j.esd.2012.10.010

Jiménez, M., Franco, C. J., & Dyner, I. (2016). *Diffusion of renewable energy technologies: the need for policy*.

Jolly, S. (2017). Energy for Sustainable Development Role of institutional entrepreneurship in the creation of regional solar PV energy markets : Contrasting developments in Gujarat and West Bengal. *Energy for Sustainable Development*, *38*, 77–92. http://doi.org/10.1016/j.esd.2016.10.004

Jónsson, T., Pinson, P., & Madsen, H. (2010). On the market impact of wind energy forecasts. *Energy Economics*, *32*(2), 313–320. http://doi.org/10.1016/j.eneco.2009.10.018

Joskow, P. L. (2008). Incentive regulation and its application to electricity networks. *Review of Network Economics*, *7*(4), 547 – 560. Retrieved from http://economics.mit.edu/files/3623

Kahn, E. P. (1998). Numerical Techniques for Analyzing Market Power in Electricity. *The Electricity Journal*, *11*(98), 34–43. http://doi.org/10.1016/S1040-6190(98)00057-8

Karneyeva, Y., & Wüstenhagen, R. (2017). Solar feed-in tariffs in a post-grid parity world : The role of risk , investor diversity and business models. *Energy Policy*, *106*(April), 445–456. http://doi.org/10.1016/j.enpol.2017.04.005

Keay, M., Rhys, J., & Robinson, D. (2013). Chapter 2 – Electricity Market Reform in Britain: Central Planning Versus Free Markets. In *Evolution of Global Electricity Markets New Paradigms, New Challenges, New Approaches* (pp. 31–57). http://doi.org/doi:10.1016/B978-0-12-397891-2.00002-X

Khalilpour, R., & Vassallo, A. (2015). Leaving the grid: An ambition or a real choice? *Energy Policy*, *82*, 207–221. http://doi.org/10.1016/j.enpol.2015.03.005

Kind, P. (2013). Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electric Business. *Edison Electric Institute*, (January).

KPMG. (2015). *The decentralised energy transition*.

Kungl, G. (2015). Energy Research & Social Science Stewards or sticklers for change ? Incumbent energy providers and the politics of the German energy transition. *Energy Research & Social Science*, *8*, 13–23. http://doi.org/10.1016/j.erss.2015.04.009

Larsen, E. R., Dyner, I., Bedoya V, L., & Franco, C. J. (2004). Lessons from deregulation in Colombia: successes, failures and the way ahead. *Energy Policy*, *32*(15), 1767–1780. http://doi.org/10.1016/S0301-4215(03)00167-8

Larsen, P. H., Goldman, C. A., & Satchwell, A. (2012). Evolution of the U . S . energy service company industry : Market size and project performance from 1990 – 2008. *Energy Policy*, *50*, 802–820. http://doi.org/10.1016/j.enpol.2012.08.035

Laws, N. D., Epps, B. P., Peterson, S. O., Laser, M. S., & Wanjiru, G. K. (2016). On the utility death spiral and the impact of utility rate structures on the adoption of residential solar photovoltaics and energy storage. *Applied Energy*. http://doi.org/10.1016/j.apenergy.2016.10.123

Leao, R., Antunes, F., Lourenco, T., & Andrade, K. (2009). A comprehensive overview on wind power integration to the power grid. *Latin America Transactions IEEE (Revista IEEE America Latina)*, *7*(6), 620–629.

Lecuyer, O., & Quirion, P. (2013). Can uncertainty justify overlapping policy instruments to mitigate emissions? *Ecological Economics*, *93*, 177–191. http://doi.org/10.1016/j.ecolecon.2013.05.009

Lee, T., Tabors, R., & Ball, B. (1990). Energy Aftermath. *HBS Press,Cambridge,MA.*

Lehmann, P. (2013). Supplementing an emissions tax by a feed-in tariff for renewable electricity to address learning spillovers. *Energy Policy*, *61*, 635–641. http://doi.org/10.1016/j.enpol.2013.06.072

Leopold, A. (2015). Energy related system dynamic models: a literature review. *Central European Journal of Operations Research*. http://doi.org/10.1007/s10100-015-0417-4

Linares, P., Javier Santos, F., Ventosa, M., & Lapiedra, L. (2008). Incorporating oligopoly, CO2 emissions trading and green certificates into a power generation expansion model. *Automatica*, *44*(6), 1608–1620. http://doi.org/10.1016/j.automatica.2008.03.006

Lindman, Å., & Söderholm, P. (2012). Wind power learning rates: A conceptual review and meta-analysis. *Energy Economics*, *34*(3), 754–761. http://doi.org/10.1016/j.eneco.2011.05.007

Linvill, C., Shenot, J., Lazar, J., Linvill, C., Shenot, J., & Lazar, J. (2013). *Designing Distributed Generation Tariffs Well*.

Lopes, J. P., Hatziargyriou, N., Mutale, J., Djapic, P., & Jenkins, N. (2007). Integrating distributed generation into electric power systems : A review of drivers , challenges and opportunities. *Electric Power Systems Research*, *77*(9), 1189–1203. http://doi.org/10.1016/j.epsr.2006.08.016

López, J., & Steininger, K. W. (2015). Photovoltaic self-consumption regulation in Spain: profitability analysis and alternative regulation schemes. *Graz Economics Papers*, (October).

Mahajan, V., Muller, E., & Bass, F. M. (1990). New product diffusion models in marketing: A review and directions for research. *Journal of Marketing*, *54*, 125–177.

Maurer, L. T. A., & Barroso, L. A. (2011). *Electricity Auctions: An Overview of Efficient Practices*.

Mercados energeticos consultores. (2014). *Revisiòn de las metodologìas de remuneraciòn de las actividades de distribuciòn y transmisiòn de energìa elèctrica*. Bogotà.

Ministerio de Industria Energía y Turismo de España. Real Decreto 900/2015, de 9 de octubre, por el que se regulan las condiciones administrativas, técnicas y económicas de las modalidades de suministro de energía eléctrica con autoconsumo y de producción con autoconsumo., BOE 27548–27562 (2015).

Ministry of Economic Affairs. (2015). *Market Study : PV Energy in Brazil*. São Paulo.

Minnaar, U. J. (2016). Regulatory practices and Distribution System Cost impact studies for distributed generation : Considerations for South African distribution utilities and regulators. *Renewable and Sustainable Energy Reviews*, *56*, 1139–1149. http://doi.org/10.1016/j.rser.2015.12.015

MME, & EPE. (2015). *Plano Decenal de Expansão de Energia 2024*.

Moreno, F., & Martínez-Val, J. M. (2011). Collateral effects of renewable energies deployment in Spain: Impact on thermal power plants performance and management. *Energy Policy*, *39*(10), 6561–6574. http://doi.org/10.1016/j.enpol.2011.07.061

Muaafa, M., Adjali, I., Bean, P., Fuentes, R., Kimbrough, S. O., & Murphy, F. H. (2017). Energy Research & Social Science Can adoption of rooftop solar panels trigger a utility death spiral ? A tale of two U . S . cities. *Energy Research & Social Science*, *34*(October 2013), 154–162. http://doi.org/10.1016/j.erss.2017.06.041

Muhammad-sukki, F., Ramirez-iniguez, R., Bakar, A., Hajar, S., Yasin, M., Abu-bakar, S. H., … Stewart, B. G. (2013). Revised feed-in tariff for solar photovoltaic in the United Kingdom : A cloudy future ahead ? *Energy Policy*, *52*(2013), 832–838. http://doi.org/10.1016/j.enpol.2012.09.062

Nelson, H. T. (2008). Planning implications from the interactions between renewable energy programs and carbon regulation. *Journal of Environmental Planning and Management*, *51*(4), 581–596. http://doi.org/10.1080/09640560802117101

Newbery, D. (2006). Chapter 4. Electricity liberalization in Britain and the evolution of market design. In *Electricity market reform: An international perspective.*

Newbery, D. (2011). Reforming competitive electricity markets to meet environmental targets. *CambridgeWorking Paper in Economics 1154*, pp. 1–16.

Newbery, D. M. (2002). Regulatory challenges to European electricity liberalisation, *9*, 9–43.

Nisar, A., Ruiz, F., & Palacios, M. (2013). Organisational learning, strategic rigidity and technology adoption: Implications for electric utilities and renewable energy firms. *Renewable and Sustainable Energy Reviews*, *22*, 438–445. http://doi.org/10.1016/j.rser.2013.01.039

Nissen, W., & Williams, S. (2016). The link between decoupling and success in utility-led energy ef fi ciency. *The Electricity Journal*, *29*(2), 59–65. http://doi.org/10.1016/j.tej.2016.02.003

Noll, D., Dawes, C., & Rai, V. (2014). Solar Community Organizations and active peer effects in the adoption of residential PV. *Energy Policy*, *67*, 330–343. http://doi.org/10.1016/j.enpol.2013.12.050

Ofgem. (2016). FIT tariff rates. Retrieved November 3, 2016, from https://www.ofgem.gov.uk/environmental-programmes/fit/fit-tariff-rates

Ofgem. (2017). Changes to the FIT scheme. Retrieved April 13, 2017, from https://www.ofgem.gov.uk/environmental-programmes/fit/about-fit-scheme/changes-fit-scheme

Oliva H., S., Macgill, I., & Passey, R. (2016). Assessing the short-term revenue impacts of residential PV systems on electricity customers, retailers and network service providers. *Renewable and Sustainable Energy Reviews*, *54*, 1494–1505. http://doi.org/10.1016/j.rser.2015.10.094

Olsina, F. (2005). *Long-Term Dynamics of Liberalized Electricity Markets*. Universidad Nacional de San Juan.

Ortega-izquierdo, M., & Del Río, P. (2016). Benefits and costs of renewable electricity in Europe. *Renewable and Sustainable Energy Reviews*, *61*, 372–383. http://doi.org/10.1016/j.rser.2016.03.044

Osterwalder, A., & Pigneur, Y. (2009). *Business model generation. A Handbook for Visionaries, Game Changers, and Challenger*.

Otero-Novas, I., Meseguer, C., Batlle, C., & Alba, J. (2000). A simulation model for a competitive generation market. *IEEE Transactions on Power Systems*, *15*, 250–257.

Overholm, H. (2015). Spreading the rooftop revolution : What policies enable. *Energy Policy*, *84*, 69–79. http://doi.org/10.1016/j.enpol.2015.04.021

Palmer, K., Paul, A., Woerman, M., & Steinberg, D. C. (2011). Federal policies for renewable electricity:

Impacts and interactions. *Energy Policy*, *39*(7), 3975–3991. http://doi.org/10.1016/j.enpol.2011.01.035

Passey, R., Watt, M., & Morris, N. (2013). *A Distributed Energy Market: Consumer & Utility Interest, and the Regulatory Requirements*.

Pepermans, G., Driesen, J., Haeseldonckx, D., Belmans, R., & D, W. (2005). Distributed generation : definition , benefits and issues $, *33*, 787–798. http://doi.org/10.1016/j.enpol.2003.10.004

Pereira, A. J. C., & Saraiva, J. T. (2013). A long term generation expansion planning model using system dynamics – Case study using data from the Portuguese/Spanish generation system. *Electric Power Systems Research*, *97*, 41–50. http://doi.org/10.1016/j.epsr.2012.12.001

Pérez, E., & Osorio, J. A. (2002). Energía, Pobreza y Deterioro Ecológico en Colombia: Introducción a las Energías Alternativas. *Todográficas*.

Pérez-Arriaga, I. J., Ruester, S., Schwenen, S., Battle, C., & Glachant, J.-M. (2013). *From Distribution Networks to Smart Distribution Systems: Rethinking the Regulation of European Electricity DSOs*. Retrieved from http://cadmus.eui.eu/handle/1814/27615

Picciariello, A. (2015). *Impact of Economic Regulation on Distributed Generation Integration in Electricity Distribution Grids*.

Picciariello, A., Reneses, J., Frias, P., & Söder, L. (2015). Distributed generation and distribution pricing : Why do we need new tariff design methodologies ? *Electric Power Systems Research*, *119*, 370–376. http://doi.org/10.1016/j.epsr.2014.10.021

Picciariello, A., Vergara, C., Reneses, J., Frías, P., & Söder, L. (2015). Electricity distribution tariffs and distributed generation: Quantifying cross-subsidies from consumers to prosumers. *Utilities Policy*, *37*, 23–33. http://doi.org/10.1016/j.jup.2015.09.007

Poisson-de Haro, S., & Bitektine, A. (2014). Global sustainability pressures and strategic choice: The role of firms' structures and non-market capabilities in selection and implementation of sustainability initiatives. *Journal of World Business*. http://doi.org/10.1016/j.jwb.2014.10.009

Pollitt, M. G., & Haney, A. B. (2013). Dismantling a Competitive Electricity Sector: The UK's Electricity Market Reform. *The Electricity Journal*, *26*(10), 8–15.

Poullikkas, A. (2013). A comparative assessment of net metering and feed in tariff schemes for residential PV systems. *Sustainable Energy Technologies and Assessments*, *3*, 1–8.

http://doi.org/10.1016/j.seta.2013.04.001

Qudrat-ullah, H. (2015). Modelling and Simulation in Service of Energy Policy. *Energy Procedia*, *75*, 2819–2825. http://doi.org/10.1016/j.egypro.2015.07.558

Qudrat-Ullah, H., & Seong, B. S. (2010). How to do structural validity of a system dynamics type simulation model: The case of an energy policy model. *Energy Policy*, *38*(5), 2216–2224. http://doi.org/10.1016/j.enpol.2009.12.009

Quiceno, G., Álvarez, C., Ávila, R., Fernández, O., Franco, Carlos Jaime Kunc, M., & Dyner, I. (2017). Scenario analysis for utility strategy under the technology transformation of the electricity industry in Colombia. *Series Utadeo*.

Rao, K. U., & Kishore, V. V. N. (2010). A review of technology diffusion models with special reference to renewable energy technologies. *Renewable and Sustainable Energy Reviews*, *14*(3), 1070–1078. http://doi.org/10.1016/j.rser.2009.11.007

Rathmann, M. (2007). Do support systems for RES-E reduce EU-ETS-driven electricity prices? *Energy Policy*, *35*(1), 342–349. http://doi.org/10.1016/j.enpol.2005.11.029

Ren21. (2016). *Renewables 2016 global status report*. Retrieved from http://www.ren21.net/wp-content/uploads/2016/06/GSR_2016_Full_Report_REN21.pdf

REN21. (2016). *Renewables global status report 2016*. Paris.

Richter, M. (2012). Utilities' business models for renewable energy: A review. *Renewable and Sustainable Energy Reviews*, *16*(5), 2483–2493. http://doi.org/10.1016/j.rser.2012.01.072

Richter, M. (2013a). Business model innovation for sustainable energy: German utilities and renewable energy. *Energy Policy*, *62*, 1226–1237. http://doi.org/10.1016/j.enpol.2013.05.038

Richter, M. (2013b). German utilities and distributed PV: How to overcome barriers to business model innovation. *Renewable Energy*, *55*, 456–466. http://doi.org/10.1016/j.renene.2012.12.052

Rifkin, J. (2015). *Industrial Revolution*. Retrieved from http://thethirdindustrialrevolution.com

Rodríguez Ortega, M. P., Pérez-Arriaga, J. I., Abbad, J. R., & González, J. P. (2008). Distribution network tariffs: A closed question? *Energy Policy*, *36*, 1712–1725. http://doi.org/10.1016/j.enpol.2008.01.025

Romero, S., & Rudnick, H. (2015). Stabilization fund for energy prices to promote renewable energy. *Latin America Transactions IEEE (Revista IEEE America Latina)*, *13*(3), 687–697.

Röpke, L. (2013). The development of renewable energies and supply security: A trade-off analysis. *Energy Policy*, *61*, 1011–1021. http://doi.org/10.1016/j.enpol.2013.06.015

Ruester, S., Schwenen, S., Batlle, C., & Pérez-arriaga, I. (2014). From distribution networks to smart distribution systems : Rethinking the regulation of European electricity DSOs. *Utilities Policy*, *31*, 229–237. http://doi.org/10.1016/j.jup.2014.03.007

Sáenz de Miera, G., del Río González, P., & Vizcaíno, I. (2008). Analysing the impact of renewable electricity support schemes on power prices: The case of wind electricity in Spain. *Energy Policy*, *36*(9), 3345–3359. http://doi.org/10.1016/j.enpol.2008.04.022

Sakhrani, V., & Parsons, J. E. (2010). ELECTRICITY NETWORK TARIFF ARCHITECTURES A Comparison of Four OECD Countries, (July).

Satchwell, A., Mills, A., & Barbose, G. (2015a). Quantifying the financial impacts of net-metered PV on utilities and ratepayers. *Energy Policy*, *80*, 133–144. http://doi.org/10.1016/j.enpol.2015.01.043

Satchwell, A., Mills, A., & Barbose, G. (2015b). Regulatory and ratemaking approaches to mitigate financial impacts of net-metered PV on utilities and ratepayers. *Energy Policy*, *85*, 115–125. http://doi.org/10.1016/j.enpol.2015.05.019

Sauter, R., & Watson, J. (2007). Strategies for the deployment of micro-generation: Implications for social acceptance. *Energy Policy*, *35*(5), 2770–2779.

Schallenberg-Rodriguez, J., & Haas, R. (2012). Fixed feed-in tariff versus premium: A review of the current Spanish system. *Renewable and Sustainable Energy Reviews*, *16*(1), 293–305. http://doi.org/10.1016/j.rser.2011.07.155

Schleicher-Tappeser, R. (2012). How renewables will change electricity markets in the next five years. *Energy Policy*, *48*, 64–75. http://doi.org/10.1016/j.enpol.2012.04.042

Schmidt, J., Cancella, R., & Pereira, A. O. (2016). An optimal mix of solar PV , wind and hydro power for a low-carbon electricity supply in Brazil. *Renewable Energy*, (85), 137–147. http://doi.org/10.1016/j.renene.2015.06.010

Schoettl, J., & Lehmann-Ortega, L. (2011). *Photovoltaic business models: threat or opportunity for utilities? Handbook of research on energy entrepreneurship. Edward Elgar, Cheltenham*.

SEIA. (2013). *Net Energy Metering Guiding Principles*. Washington, D.C. Retrieved from http://www.seia.org/research-resources/net-energy-metering-guiding-principles

Sensfuß, F., Ragwitz, M., & Genoese, M. (2008). The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. *Energy Policy*, *36*(8), 3086–3094. http://doi.org/10.1016/j.enpol.2008.03.035

Severance, C. a. (2011). A practical, affordable (and least business risk) plan to achieve " 80% clean electricity" by 2035. *Electricity Journal*, *24*, 8–26. http://doi.org/10.1016/j.tej.2011.06.004

Shah, A. N., Palacios, M., & Ruiz, F. (2013). Strategic rigidity and foresight for technology adoption among electric utilities. *Energy Policy*, *63*, 1233–1239. http://doi.org/10.1016/j.enpol.2013.08.013

Sioshansi, F. P. (2014). Decentralized Energy: Is It as Imminent or Serious as Claimed? In F. P. Sioshansi (Ed.), *Distributed Generation and its Implications for the Utility Industry* (pp. 3–32).

Sioshansi, F. P. (2015). Electricity utility business not as usual. *Economic Analysis and Policy*, *48*, 1–11. http://doi.org/10.1016/j.eap.2015.11.015

Sioshansi, F. P. (2016). Chapter 1. What is the future of the electric power sector? In *Future of Utilities-Utilities of the Future: How Technological Innovations in Distributed Energy Resources Will Reshape the Electric Power Sector* (pp. 2–23).

Skytte, K. (2006). Robert Schuman Centre for Advanced Studies - Working paper 2006/04 - Klaus Skytte. *EUI WORKING PAPERS*.

Stenzel, T., & Frenzel, A. (2008). Regulating technological change—The strategic reactions of utility companies towards subsidy policies in the German, Spanish and UK electricity markets. *Energy Policy*, *36*(7), 2645–2657. http://doi.org/10.1016/j.enpol.2008.03.007

Sterman, J. (2002). All models are wrong: reflections on becoming a systems scientist. *System Dynamics Review*, *16*(4), 501–531.

Sterman, J. D. (2000). *Business Dynamics. Systems Thinking and Modeling for a Complex World*. United States: McGraw-Hill Higher Education.

Sterman, J. D. (2000). *Business dynamics: systems thinking and modeling for a complex world*. Boston: Irwin/McGraw-Hill.

Strupeit, L., & Palm, A. (2015). Overcoming barriers to renewable energy diffusion : business models for customer-sited solar photovoltaics in Japan , Germany and the United States. *Journal of Cleaner Production*, 1–13. http://doi.org/10.1016/j.jclepro.2015.06.120

SUI. (2015). Sistema Único de Información de Servicios Públicos Domiciliarios. Servicio de Energía. Reportes. Retrieved June 17, 2016, from http://www.sui.gov.co/SUIAuth/portada.jsp?servicioPortada=4

Taylor, M., Ralon, P., & Ilas, A. (2016). *The power to change: solar and wind cost reduction potential to 2025*.

Thema, J., Suerkemper, F., Grave, K., & Amelung, A. (2013). The impact of electricity demand reduction policies on the EU-ETS: Modelling electricity and carbon prices and the effect on industrial competitiveness. *Energy Policy*, *60*, 656–666. http://doi.org/10.1016/j.enpol.2013.04.028

Timilsina, G. R., Kurdgelashvili, L., & Narbel, P. A. (2012). Solar energy : Markets , economics and policies. *Renewable and Sustainable Energy Reviews*, *16*(1), 449–465. http://doi.org/10.1016/j.rser.2011.08.009

Tongsopit, S., Moungchareon, S., Aksornkij, A., & Potisat, T. (2016). Business models and fi nancing options for a rapid scale-up of rooftop solar power systems in Thailand. *Energy Policy*, 1–11. http://doi.org/10.1016/j.enpol.2016.01.023

Tveten, Å. G., Bolkesjø, T. F., Martinsen, T., & Hvarnes, H. (2013). Solar feed-in tariffs and the merit order effect : A study of the German electricity market. *Energy Policy*, *61*, 761–770. http://doi.org/10.1016/j.enpol.2013.05.060

Unger, T., & Ahlgren, E. O. (2005). Impacts of a common green certificate market on electricity and CO2-emission markets in the Nordic countries. *Energy Policy*, *33*(16), 2152–2163. http://doi.org/10.1016/j.enpol.2004.04.013

UPME. (2005). *Unidad de Planeación Minero Energética. Atlas de Radiación solar de Colombia*.

UPME. (2015). Plan Energético Nacional Colombia: Ideario Energético 2015. Bogotá.

Ventosa, M., Baíllo, Á.´, Ramos, A., & Rivier, M. (2005). Electricity market modeling trends. *Energy Policy*, *33*, 897–913. http://doi.org/10.1016/j.enpol.2003.10.013

Vogel, P. (2009). Efficient investment signals for distributed generation. *Energy Policy*, *37*(9), 3665–3672. http://doi.org/10.1016/j.enpol.2009.04.053

Wainstein, M. E., & Bumpus, A. G. (2016). Business models as drivers of the low carbon power system transition : a multi-level perspective. *Journal of Cleaner Production*, *126*, 572–585. http://doi.org/10.1016/j.jclepro.2016.02.095

Watts, D., Valdés, M. F., Jara, D., & Watson, A. (2015). Potential residential PV development in Chile : The effect of Net Metering and Net Billing schemes for grid-connected PV systems. *Renewable and Sustainable Energy Reviews*, *41*, 1037–1051. http://doi.org/10.1016/j.rser.2014.07.201

Wiebe, K. S., & Lutz, C. (2016). Endogenous technological change and the policy mix in renewable power generation. *Renewable and Sustainable Energy Reviews*, *60*, 739–751. http://doi.org/10.1016/j.rser.2015.12.176

Wu, J.-H., & Huang, Y.-H. (2014). Electricity portfolio planning model incorporating renewable energy characteristics. *Applied Energy*, *119*, 278–287. http://doi.org/10.1016/j.apenergy.2014.01.001

XM. (2015). Los Expertos en Mercados, Plataforma de datos Portal BI. Retrieved June 17, 2016, from http://informacioninteligente10.xm.com.co/Pages/default.aspx

Yamamoto, Y. (2012). Pricing electricity from residential photovoltaic systems: A comparison of feed-in tariffs, net metering, and net purchase and sale. *Solar Energy*, *86*(9), 2678–2685. http://doi.org/10.1016/j.solener.2012.06.001

Zahedi, A. (2010). A review on feed-in tariff in Australia , what it is now and what it should be. *Renewable and Sustainable Energy Reviews*, *14*(9), 3252–3255. http://doi.org/10.1016/j.rser.2010.07.033

Zhang, S. (2016). Innovative business models and fi nancing mechanisms for distributed solar PV (DSPV) deployment in China. *Energy Policy*, 1–10. http://doi.org/10.1016/j.enpol.2016.01.022

Zuluaga, M. M., & Dyner, I. (2007). Incentives for renewable energy in reformed Latin-American electricity markets: the Colombian case. *Journal of Cleaner Production*, *15*, 153–162. http://doi.org/10.1016/j.jclepro.2005.12.014