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Diffusion of renewable energy technologies: The need for policy in Colombia

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A B S T R A C T

Although the diffusion of solar electricity has been swift worldwide, there is little certainty regarding the adoption of this technology on rooftops, in locations where there is no specific policy on renewables in place. In such cases, there is much uncertainty regarding the effect of solar penetration on electricity prices to consumers and on the reduction of electricity demand from the grid. The penetration of solar in the residential sector – which in some cases accounts for about 40% of the country's total electricity demand – may have a tremendous impact on incumbent utilities and the industry as a whole. Much research has been devoted to assessing the effect of policy on the diffusion of renewables but not much work about the developing world is known, particularly in those nations where institutional arrangements do not favour these technologies. Using system dynamics, this paper examines these issues, considering the diffusion of rooftop solar both with a battery support system, and also without any type of storage system. An important conclusion is that policy is essential for system sustainability when PV diffusion is taking place.

1. Introduction

An international outlook on the progress of Photovoltaics (hereinafter PV, see Table A1 for all abbreviations), in recent years, shows that this alternative for energy generation has been increasing in both cumulative capacity (GW) and in generation capacity (TWh). The International Energy Agency (IEA) [1], in its *Solar Photovoltaic Energy* report, shows that the cumulative global PV capacity has been increasing at an average rate of 49% per year, in recent years. Moreover, the IEA's *Medium-Term Renewable Energy Market Report 2014* [2] shows how PV generation is increasing in different regions and that this trend is expected to continue in the near future.

Rapid increases in cumulative and generation PV-capacity can be explained three ways: first, by the intrinsic benefits of PV technology, which have motivated its adoption because of its simple power generation process [3] and its environmental friendliness [3,4]; second, by the reduction of PV systems' production costs [4], as the technology learning curves have made impressive progress since the beginning of the century; these reducing costs are expected to continue to progress in the mid-term [5], which will further improve the perceived benefit of PV systems; and lastly, as policy is seeking alternative power generation technologies as a way to face different issues regarding environmental problems, geopolitical instability and price volatility of fossil fuels [6], policy has played a significant motivating role for rooftop adopters, by subsidizing the implementation of PV systems [3].

Despite the benefits of solar generation, governments are concerned about the rapid increases in the technology's diffusion for two reasons: first, as this has exceeded initial expectations in a number of countries that implemented favourable policies, such as the United Kingdom, Spain and Germany [7–11]; a second concern is that this growth has affected the stability of the interconnected system, prompting redefinitions of the incentive structures in order to control solar diffusion and its effects on market stability [2,12–14]. However, in many regions in the developing world, where poor people have little access to electricity, there is considerable opportunity to take advantage of this technology.

Against the preceding background, this paper examines what may happen in electricity markets where policy is being considered or is in early stages of implementation, by exploring unintended

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and undesirable consequences by means of simulation experiments. To examine the issue, this paper develops a simulation model built to assess, under two scenarios, the effects of the diffusion of PV in the residential sector of an electricity market, considering: first, the standard diffusion of PV systems that maintain some support from the electricity grid and, second, PV systems with storage support but no grid support, which provides the householder with grid independence.

Colombia has been selected as the application case, given that this is a country with favourable conditions for PV generation – PV is cost competitive with the grid tariff [15] – and also that despite the recently promulgated Law 1715 [16], which favours renewables, there is much uncertainty concerning its implementation and particularly regarding its effect on the rate of adoption, on prices and on security of supply issues in the Colombian energy market.

The focus is on the residential rooftop solar generation sector in Colombia as: a) the residential sector contributes about 40% of the total electricity demand [17], b) 70% of all dwellings are houses [18], and c) a large percentage of dwellings can easily install microgeneration PV systems. Some of the lessons from the Colombian case might also be applicable in other situations and countries.

To reach the proposed objective, this paper is organized as follows: Section 2 provides a review of the international experience on renewables' diffusion, Section 3 describes the Colombian energy market and Section 4 describes the implemented system dynamics (SD)-based model. Section 5 presents the main simulation results, Section 6 reports validation and conducts a sensitivity analysis, and finally Section 7 presents the conclusions of this work.

2. International experiences of the diffusion of renewables

A number of papers examine the impact of the diffusion of renewables on electricity markets, from aspects such as: consumption habits, supply intermittency and transmission system balance. In this direction, Balcombe, Rigby & Azapagic [19] indicate that the high diffusion of renewables in the United Kingdom has caused problems regarding grid intermittency and market balance; similarly, der Veen & De Vries [20] illustrate market efficiency and reliability problems in the Dutch case. In the Spanish context, while utilities experience reductions in revenues and profits, households experience increases in electricity tariffs [21]. Widén [22] and Keirstead [23] show that while in Sweden users change their consumption habits by increasing electricity consumption when using renewables, conversely, United Kingdom (UK) households using renewables reduce their electricity demand.

Many countries use different policies to promote renewables [2,24]. Feed-in Tariffs (FITs) have been used with good results in Japan, Germany, the United Kingdom and Spain, among many others [3,7,9,10,25,26]. Other incentives, elsewhere, have focused on financial incentives such as Green Certificates [7,10] or Net Metering [21].

Nevertheless, there are still countries, especially in emerging economies, which do not actively promote the diffusion of renewables and, further, which maintain market barriers to their dissemination, despite their countries' potential for use of renewables. In Latin American countries for example, the potential of renewables including PV has been recognized at both utility and residential scale, highlighting their beneficial irradiance availability and financial competitiveness as compared with other technologies [2,27,28]. Mexico, Brazil, Argentina, Chile, Peru, Colombia, Guatemala, Ecuador and Venezuela were included in the European Photovoltaic Industry Association (EPIA) PV opportunity mapping of the Sunbelt, according to their solar resource and investment attractiveness [28]. However PV installations remain low in most of these countries, even though Mexico, Peru, Brazil and Chile stand out because of their current installations and expected progress [28,29].

An important reason for the low PV deployment in the Latin American and Caribbean countries is, according to Jacobs et al. [29], bad policy design that is not appropriate for the specific country conditions or are non-attractive to investors. In this sense, Shirley and Kammen [30] explain the importance of favourable policy, designed according to the particulars of the countries concerned. Some of the regulatory framework for renewables in Latin American countries includes Renewable Portfolio Standard or RPS (for example, Peru), targets (such as in Argentina, Brazil, Colombia, Nicaragua and Uruguay) and a combination of RPS, targets and a renewable energy law (as in Chile and Mexico) [2]. In particular, though Colombia promulgated law 1715 in May 2014 [16], it has not been yet fully implemented.

This paper identifies some of the effects of the penetration of PVs on electricity markets, where there are favourable conditions but no clear incentives. The focus here is on the number of households that may adopt PV systems and on the load duration curves as well as on the electricity tariff from the grid. These effects are assessed under two scenarios: PV system with batteries as a storage mechanism, and PV systems without storage but with the support of electricity from the grid, aiming in both scenarios to identifying changes in electricity demand patterns.

To analyse diffusion problems, there are two main alternative levels of analysis reported in the literature: the micro and the macro level [31]. At the micro level of analysis, the different authors consider agent based, cellular automata and percolation modelling, where the unit of analysis is a single individual considering his/her perception of relative advantages and disadvantages of technology adoption, and the influence exerted by neighbours [31].

At the macro level, the unit of analysis is the aggregated social system or community, and the focus is on market size and the adoption time [31]. This perspective includes methodologies such as system dynamics, which consider the combined complex behaviour of a set of individuals characterized by their collective behaviour, and represented by accumulated variables [32].

This paper uses the macro-level perspective, with the support of a system dynamics model of several well-known system characteristics, including a) system complexity, b) variable accumulation, c) feedbacks, and d) delays [33–35]. Furthermore, SD has been largely used in policy assessment in related energy applications [11,36–41], including photovoltaics policy analysis [42].

3. The Colombian electricity market

The Colombian power market is highly liberalized (open to competition) through the electricity supply chain, except for the household sector, which is regulated via a tariff mechanism and supplied by the local utility [43]. As previously noted, the residential sector in Colombia consumes about 40% of the total electricity generated, and about 70% of residences are houses, rather than flats in apartment blocks. Further, in Colombia, about 96% of the population has regular access to electricity [44,45].

Average electricity consumption of households in Colombia reaches 153.96 kWh/month (calculation with data from Refs. [46,47]). Fig. 1 shows the average hourly load curve profile for an average day in the Colombian Electricity Market, and Fig. 2 shows the specific hourly load curve profile for the residential sector in Colombia.

The electricity tariff in the household sector for the main cities was between USD 0.124 and USD 0.139 in 2014 (using data from Ref. [17] and an exchange rate of 3000 COP/USD). This tariff is calculated as the sum of: the generation price and the costs of trading, losses, restrictions, and distribution and transmission