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Renewable energy technology diffusion: an analysis of photovoltaic-system support schemes in Medellín, Colombia

Amando A. Radomes Jr. [a, 1], Santiago Arango [b, *]

[a] Department of Industrial Engineering, University of San Carlos – Technological Center, Nasipit Talamban, Cebu City, Philippines
[b] Department of Computing and Decision Sciences, Universidad Nacional de Colombia – Sede Medellín, Carrera 80 No. 65-223, Bloque M8A, Medellín, Colombia

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ABSTRACT

Colombia's electricity mix is dominated by hydropower, which constitutes over 65 percent of the installed capacity. The country has important potential for introducing solar photovoltaic sources into its electricity generation mix given its high average annual insolation. However, there is a lack of incentives and support schemes for alternative renewable energy technologies. This paper analyzes the diffusion of a photovoltaic system in Colombia with a focus on Medellín, Colombia's second largest city. A diffusion model is constructed, based on the classic Bass diffusion theory, where the adoption rate is a function of awareness-raising campaigning and social interaction. The model incorporates both subsidy and feed-in-tariff policies. Policy implementation scenarios and the effects of policy mixes are analyzed. Results show that a 50 percent subsidy for investment, together with a USD 0.30/kWh feed-in-tariff rate, jointly provide the highest marginal increase in diffusion rate. However, given the cheapness of the country's current hydroelectric resources, photovoltaic-system diffusion might remain a challenge for both the government and private sectors for the foreseeable future.

1. Introduction

Article 2 of the Kyoto Protocol framework aims for the implementation of policies for research and development of renewable energy (RE) resources, carbon sequestration technologies, and innovative environmentally-friendly technologies (UN, 1998). The 2002 World Summit on Sustainable Development at Johannesburg sought to review the achievements of the decade-old and laid down plans for implementation. Although no concrete targets for the increased consumption of RE resources have been established (WHO, 2013), such initiatives have influenced many countries' perspectives on the development of RE (ECLAC, 2004). At the summit's culmination, Colombia joined another 81countries in establishing the Johannesburg Renewable Energy Coalition (JREC) that aimed to "*focus on international, regional, and national political initiatives that will help foster policies for the promotion of renewable energy*" (Europa, 2013). Three years after the Johannesburg Summit, 55 countries had adopted one or more RE policies. Six years later, this figure had grown to almost 120 (REN21, 2011). A variety of RE policies have been implemented in Colombia since the 1992 Rio Conference (IRENA, 2012). In parallel to the Colombian government's interest in RE, this paper investigates the diffusion of PV system, particularly in Medellín, the country's second largest city.

Colombia is located in the northern region of South America, bordering the Caribbean Sea, between Panama and Venezuela, and bordering the North Pacific Ocean, between Ecuador and Panama. Its total area is 1,138,900 km^2 with a tropical climate along the coast and eastern plains, while lower temperatures are experienced in the highlands (DANE, 2013). Population estimates in 2012 for Medellín were 2.743 million for the city and 3.590 million for the metropolitan area, with an annual population growth rate of 1.13 percent (CIA, 2013). In 2005, Medellín city had 612,115 households; in 2012, the number of inhabitants was estimated to be 783,000 (DANE, 2013). Hydropower is Colombia's major source of electricity generation, making up over 67 percent of its total electricity production in 2009 (Loy and Gaube, 2002; UPME, 2013). The relative proportion of each source has not changed significantly since the early 1990s (UPME, 2013). In 2009, 41.7 TWh (72.8 percent) of Colombia's 57.3 TWh of generated electricity, came from renewable resources (IRENA, 2012).

* Corresponding author. Tel.: +57 4 4255371.
E-mail addresses: amando.radomes@gmail.com (A.A. Radomes), saarango@unal.edu.co (S. Arango).
[1] Tel.: +63322300100x256.

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In 2001, the Colombian Congress signed the *Ley 697 de 2001* (Law 697 of 2001) that promotes an efficient use of energy and the use of alternative energy sources (MinMinas, 2003). Thereafter, subsequent laws focused on targeting goals, tax exemptions, investment in research, and reliability-charge exemptions for small projects (IADB, 2010). Such initiatives were not effective in the deployment of RE resources because of the lack of support schemes (Ruiz-Mendoza and Sheinbaum-Pardo, 2010). For instance, Resolution 181,401/2004 (MinMinas, 2004) sets a target for CO_2 emission reduction through the use of non-conventional energy resources; however, no specific guidelines are mentioned regarding the incentives for installing a particular RE technology (RET), the kind of support a particular government agency will provide, or the timeline to reach the target. Existing policies are mostly limited to biofuels, CO_2 emission reduction, and encouragement of energy efficiency. Though overall targets are set, the legislation does not specify how the goals are to be reached.

The Colombian power system was restructured in the mid-1990s, moving from a government monopoly to a market-oriented structure (IADB, 2010), which also drew the attention of scholars interested in electricity deregulation. Thus, several studies have focused on understanding post-deregulation scenarios (Arango et al., 2006; Arango, 2007; Larsen et al., 2004); while others have centered on the adoption of RET in the liberalized market. For instance, Zuluaga and Dyner (2007) constructed a simulation model to analyze different policies that may encourage the adoption of RE in Colombia. Though they explored two alternative technology diffusion scenarios, they aggregated all RE resources into a cumulative installed capacity. Botero et al. (2009) used MARKAL (Market Allocation Model) to identify the optimal contribution of energy mixes to a cost minimization objective function. Lund et al. (2014) investigated how energy system in cities could used as a carbon reduction strategy. The first grid-connected building featuring a photovoltaic system installation in Colombia was studied by Aristizábal and Gordillo (2008); but their experiment was limited to the technical feasibility, looking into the array, the inverter, and the system performance of the PV system.

South America is the region with the highest share of electrical production from renewable resources worldwide (Enerdata, 2012; Observ'ER, 2012). When it comes to solar energy, Chile and Brazil have the largest installations, with 51 and 37 percent, respectively, of the total PV capacity in the region (Solarbuzz, 2013). Chile's dominance in the South American PV market can be explained partly by effective energy policy (Choudhury, 2013; MinEnergia, 2012) rather than by the potential of PV power. Varieties of RE policies have been implemented already or are planned for Latin America, such as:

- *Ecuador:* The national electricity board, CONELEC, implemented a feed-in tariff (FiT) policy in April 2011. The program includes tariffs for wind, biomass, biogas, geothermal and hydroelectric plants up to 50 MW in size (Choudhury, 2013; CONELEC, 2011).
- *Argentina:* The government's target is to reach an eight percent share of its energy mix with renewable resources by 2016. It has a FiT system for solar power implemented through a national fund for the promotion of RE (Choudhury, 2013).
- *Mexico:* A renewable energy bill aims to reach a 35 percent target for use of RE resources by 2024. Tax incentives for solar projects and a net metering system have been implemented (Bissegger, 2013; Choudhury, 2013).
- *Brazil:* PV projects of $\leq$1 MW are being planned in preparation for the 2016 Olympics. Its electricity regulatory agency, ANEEL, is preparing to implement two new solar incentive policies: an 80 percent reduction in taxes and the implementation of net metering for residential and commercial installations (Bissegger, 2013; Choudhury, 2013).
- *Chile:* There are 3.9 MW of PV projects installed and another 30 MW currently under construction (Lacey, 2013). Act 20,257 requires electrical utilities with an installed capacity of over 200 MW to obtain part of the energy they sell to customers from RE resources (Choudhury, 2013). A law on net metering is currently in Congress pending approval (MinEnergia, 2012).

Although the global average of RE production cost has drastically decreased in the past decade, developing countries' adoption of the technology vary significantly (Huenteler et al., 2014; Jänicke, 2012). Table 1 shows Colombia's potential for harnessing a wide range of RE (ECLAC, 2004). While countries that experience four distinct seasons have electricity consumption peaks during the coldest and warmest months of the year (Farmington, 2013; StatCanada, 2010), tropical countries like Colombia have a relatively constant temperature and seasonal pattern and, therefore, have more stable energy consumption throughout the year. With solar energy, the average radiation is 4.5 kWh/m^2/day and the best solar resource area is the Guajira Peninsula, with insolation of 6 kWh/m^2/day (UPME, 2002). In contrast, while Germany has the largest installed PV capacity in the world, at 24.8 GW as of 2011, it produces only around 3.8 kWh/m^2/day at its peak, in Kempten in the Allgäu region, which has already the highest solar potential in the country (European Commission, 2008; Meteonorm, 2007; Solarplaza, 2012).

Solar irradiance (W/m^2; and, relatedly: insolation, kWh/m^2/day) is a measure of how much solar power a location receives. It varies throughout the day according to the sun's position and throughout the year depending on the season (Boxwell, 2013). On average, Medellín receives 4.57 kWh/m^2/day insolation (Table 2).

The steady decline of installed PV system costs in past decades is gradually making PV competitive in regions with high solar insolation and/or high electricity prices (IEA PVPS, 2012). Having the same advantage with other countries near the equator, Colombia receives a relatively stable amount of solar radiation throughout the year (Boxwell, 2013), providing it with high potential for solar energy. However, PV installations in Colombia remain very limited and mostly for research or experimental purposes only (Aristizábal and Gordillo, 2008; Loy and Gaube, 2002).

The main goal of this paper is to investigate the diffusion of renewable energy technologies in Colombia. Specifically, the effects of subsidy and FiT support-schemes on the deployment of PV system, with focus on the city of Medellín, are analyzed. Section 2 reviews the two support schemes included in this paper and discusses the Bass diffusion model and PV learning curve. In Section 3, the scope, assumptions, and model validation are discussed. Next, a comparison is made between the effects of different policy mixes in Section 4, including breakeven and sensitivity analyses. Finally, in Section 5, different scenarios are shown in support of the schemes. Recommendations on future research are also provided.

Table 1
Renewable energy potentials for Colombia (ECLAC, 2004).

Energy	Potential
Solar	Annual potentials from 5 to 6 kWh/m^2/day
Biomass	Annual production of cane *bagasse* is 7.5 M tons; rice husks at 457,000 tons
Wind	Over 10 m/s at the northern region
Hydro	50 GW of >100 MW capacity; 70 GW for medium and small scale
Geothermal	Greatest potential in Nariño, Los Nevados National Park, and Paipa
Tidal	Around 500 MW along the coast
Wave	Up to 30 GW along the coast