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Assessing the combined effect of the diffusion of solar rooftop generation, energy conservation and efficient appliances in households

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ABSTRACT

There is a growing worldwide concern regarding emissions of energy-related greenhouse gases (GHGs). Policy, technology and human awareness provide opportunities for offsetting these effects through energy conservation, efficient appliances and solar generation in households as these have been the subject of increasing attention across the world in recent years. Solar rooftop generation, in particular, could deliver significant efficiency improvements and reductions of CO2 emissions through its diffusion, which also avoids losses in electricity transmission and distribution systems; energy efficiency contributes to the achievement of a sustainable future because it reduces the energy-infrastructure needs, increases competitiveness and improves consumer welfare; conservation would also reduce CO2 emissions in households. The purpose of this paper is to assess the combined effect of the diffusion of solar rooftop generation, energy efficiency and electricity conservation in the residential sector in Colombia. Simulation results for different policy scenarios indicate that rooftop generation, energy efficiency and conservation can together lead, under certain conditions, to important reductions in both electricity prices and emissions.

1. Introduction

The sustained growth of modern societies, particularly dependent on fossil fuels, has been the main driver for the current environmental concerns worldwide (International Energy Agency, 2014). In response to this, and aiming at mitigating environmental impacts (Stamford and Azapagic, 2014) as well as both supporting development (Treyer and Bauer, 2016) and preserving security of electricity supply, three actions have been commonly promoted in the household sector: power generation from renewables, a shift towards more efficient domestic appliances and energy conservation (Wood and Newborough, 2003).

Energy conservation and efficiency in households can simultaneously assist in satisfying electricity demand (Gillingham et al., 2009) and also in emissions mitigation (Mattinen et al., 2014) by shifting behaviour towards habitual energy conservation and by the use of more efficient appliances in households (Yohanis, 2012). Conservation entails reducing energy consumption (Demirel, 2012), particularly when associated with thrifty lifestyles that include forms of self-regulation or spontaneous shifts of consumers' preferences, resulting in behavioural changes (Sarkis, 2017).

A sister paper (Cardenas et al., 2016) discusses the broad effect of the diffusion of renewables on CO2 emissions and electricity prices by using an integrated supply and demand approach. This paper, while retaining a comprehensive perspective, focuses on the demand-side, considering in particular the impact that energy policy may have on households and on the entire grid system as a whole. The purpose is to show how policy influences customer behaviour, which is often ignored in the energy analysis. The questions addressed in the paper include: How can policy contribute to the penetration of efficient and cleaner technologies in the household sector? And: What may be the benefits of policy to households and the electricity sector as a whole?

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Given the number of variables involved, their entangled relationships and the non-linear feed-back effects among them, the paper employs system dynamics modelling for assessing the long-term effects of policy. Furthermore, this paper chooses Colombia, the fourth largest economy in Latin America, as the case illustrating the issues involved. The reason for this choice is that although many countries in the developing world have decisively implemented energy policies incorporating renewables, Colombia has not done so, in spite of being a nation that has abundant natural energy resources. The paper assesses whether there would be beneficial effects in Colombia utilising renewables, and draws lessons for power policy.

The main objective of this research is thus a model-based assessment of the effect on the overall energy sector from the penetration of both PV rooftop generation systems and efficient electrical appliances as well as the adoption of energy-conservation practices, in the residential sector in Colombia. From a holistic perspective, this paper contributes to the evaluation of policies that promote sustainable electricity consumption in the Colombian residential sector.

The paper is organised as follows: While the following section describes the problem that is being addressed and reviews the current state of the art regarding rooftop systems, energy efficiency and energy conservation at the national level, Section 3 proposes an approach for addressing the issues posed. Section 4 discusses the model that has been built to address the problem and Section 5 states the assumptions made. Section 6 discusses results and the last section discusses results and conclusion.

2. The problem

Renewable electricity generation worldwide has been growing at a yearly average rate of 2.8% since 1990, which is less than the 3% growth of total electricity generation (International Energy Agency, 2013). However, during the recent five year period between 2010 and 2015 the yearly growth of renewables was considerably higher, at rates up to 42% in solar PV, 2.9% in hydropower, 3.7% in geothermal power, 12% in solar heating, 6.5% in biodiesel and 3% in bioethanol (REN21, 2016) – though renewable energy still only provides about 13% of the total energy supply globally (Zhang et al., 2012).

Rapid development and population growth have brought increases in energy demand, boosting the implementation of various technologies for the sustainable use of resources (Dinçer, 2011). Technology progress has promoted the penetration of renewable energy and micro-power generation. This has speeded the learning processes for these technologies, bringing down electricity prices and making them competitive in comparison to that provided from the grid in many countries around the world (grid parity) (Trappey et al., 2016).

Among the multiple potential schemes to use renewable energy sources, rooftop PV is one that contributes to autonomous electricity generation in the residential sector (Castaneda et al., 2017). PV rooftop emerges as a cost-effective option to establish new capacity and could deliver both significant efficiency and reduction of CO2 emissions (Breyer et al., 2015), through the increased use of renewables, utilisation of “waste” heat from electricity generation, and avoidance of losses in the electricity transmission and distribution system. In this new context, a large number of households may choose between generating their own electricity – thus turning into what are being called “prosumers” (Hyysalo et al., 2016; Kästel and Gilroy-Scott, 2015) – and buying their electricity from the grid.

At the global level, alternative modelling-based research has been carried out to assess the effects of microgeneration technologies, appliance efficiency and energy conservation in the residential sector. For instance, regarding microgeneration technologies, agent-based simulation has been used to assess the competition between micro-CHP and incumbent condensing boilers in the Netherlands (Faber et al., 2010); and also, to analyse policies on distributed photovoltaic (PV) systems (Zhao et al., 2011). In the same direction, discrete choice experiments have been conducted to investigate the effects of adoption of renewable micro-generation systems in South Korea (Jeong, 2013) and Canada (Islam, 2014). For the Colombian case, system dynamics simulation was used to study the diffusion of rooftop solar generation, both with and without a battery support system (Jimenez et al., 2016).

With respect to the effects of efficient appliances in residential demand, Milani et al. (2015) they examine washing machines in Western Europe; Young (2008) does likewise for refrigerators, freezers, dishwashers, clothes washers and clothes dryers in Canada; and, Ortiz et al. (2014) for a number of appliances in the Mediterranean region and Richardson et al. (2010) for the UK. However, the concern not only to evaluate the effects on energy use but also the effects on CO2 emissions has been recognised by Subramanyam et al. (2016) who conduct energy modelling and scenario analyses for Canada; van Ruijven et al. (2011) use a model for India that simulates the demand for several energy functions, such as heating and cooling, lighting and the use of appliances. For the evaluation of energy conservation measures (ECMs), Mata et al. (2015) and Wada et al. (2012), examine the measures’ impacts on net and final energy demands and their associated effects on CO2 emissions, for Spain and India, respectively.

The literature discusses the adoption dynamics of both rooftop PVs and of efficient appliances in households as well as the diffusion of conservationist habits in energy use. In addition, some research focuses on the implementation policy for sustainable energy use. However, a gap has been found in the literature as regards integrated model-based policy assessment that simultaneously considers the effect of the adoption of solar panels, efficient appliances and conservationist habits in the residential sector, especially in the developing world where income might be low and some natural resources might be abundant. This paper provides a novel approach that fills the aforementioned gap.

In Colombia, the residential sector is a substantial consumer of energy in every country and thus a focus for policy attention (Swan and Ugursal, 2009). In Colombia, the residential sector represents about 40% of total electricity consumption (SUI, 2014). Though not the largest contributor of GHGs, the residential sector provides a policy opportunity: to reduce emissions in the household sector via the diffusion of solar photovoltaic (PV) energy or energy efficiency. This would bring down overall emissions in the country, thereby reducing the pressure to produce electricity from more expensive fossil-fuel plants in the interconnected system. The argument goes as follows: as Colombia is a highly hydroelectric-based country (about 66% of dispatched electricity comes from hydroelectricity, with the rest from coal and gas-fired plants (XM, 2016)), when reducing a portion of electricity production from the interconnected system, most of the time this will bring a reduction of the dispatch from fossil-based plants (as policy intended). This will then reduce CO2 emissions from those fossil-based plants; and instead, households will be using zero-emission electricity from PV panels – the intended, positive policy consequence of reducing both costs to consumers and CO2 emissions.

This paper investigates the impact of alternative energy policy for the household sector. It seeks to establish how this impacts the domestic sector and the system as a whole, focusing on electricity price and emissions benefits. Using a model-based approach applied to Colombia, the paper aims at understanding the importance of the domestic sector’s effects on the electricity market,