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ORIGINAL ARTICLE

The rebound effect on Latin American economies: evidence from the Colombian residential sector

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Abstract Energy efficiency technologies have been promoted worldwide by policymakers and government and non-governmental institutions to decarbonize economies. In such context, Colombian government forecasted a total energy savings of around of 9% at the end of 2021 by promoting energy efficiency technologies across the different economic sectors. However, such efficiency goals may not be fully achieved due to the existence of the rebound effect. The rebound effect has the potential not only of entirely suppressing the energy savings expected but also of generating additional energy demand, a phenomenon known as backfire effect. Although the rebound effect has been extensively studied for developed countries, there is no empirical evidence of this phenomenon for South American countries. Hence, this study measures the direct rebound effect for all energy services consuming electricity in the household sector in Colombia along the period 2005–2013 by applying econometric techniques in a panel data for 15 states around the country. The results suggest a national rebound effect of 83.4% and values ranging across regions between 64.7 (Atlantico) and 78.9% (Meta). Our study points out that the rebound effect in Colombia follows a geographic patter, with high values at the interior of the country, which is relevant to various stakeholders in order to make informed decisions. Policymakers will gain knowledge on the role of the rebound effect in planning sustainability goals, whereas academics and practitioners will benefit of novel data regarding the role of the rebound effect in Latin American economies. Given the significance of our finding about rebound effect in a Latin American country, we conclude with some recommendations aimed at relevant stakeholders.

Keywords Electricity consumption · Direct rebound effect · Developing countries, Econometric analysis

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Introduction

Colombian greenhouse gas (GHG) emissions accounted for about 236.9 Mton CO_2 ((IDEAM et al., 2018) in 2014 (the last year for which such data is available at the writing of this article) and it is projected to increase by 50% in 2030 (García Arbeláez et al., 2016). Therefore, and in line with the worldwide efforts to defeat climate change, the Colombian government compromised to reduce their GHG emissions by 20% by 2030. In order to achieve such compromises, the government recently issued several political instruments. Specifically, the government issued the national climate change policy (PNCC), the Colombian Low-Carbon Development Strategy (ECDBC), the National Climate Change Adaptation Plan (PNACC), the National Strategy for Reducing Emissions from Deforestation and Forest Degradation (ENREDD+), and the National Climate Finance Strategy (ENFCC) (MADS, 2017).

One of the key strategies to consider within the PNCC is the promotion of energy savings through efficiency improvements in all the consumed energy sectors from which the residential sector has a non-negligible savings potentials. Concretely, according to estimations of the Energy Mining Planning Unit (UPME), the most important energy authority in the country, the residential sector has a savings potential of 0.73% on the energy to be consumed by 2022 (UPME, 2016a).

Colombian residential sector accounted for 38% of the 58.7 TWh consumed in 2018 and it is expected to increase by about 2% yearly until 2030 (UPME, 2016b). Also, it is worth noting that electricity accounts for 51% of the total energy consumed in this sector, followed by natural gas (35%) (see Fig. 1) (UPME, 2016a). Among energy services, the consumption of electricity is mainly triggered by refrigeration, television, and lighting (see Fig. 2) (UPME, 2016a). Cooking is carried out with natural gas, LPG, and in a lesser extend with electricity. Such increase implies challenges in terms of climate change since the electricity sector accounted for about 9% of the total greenhouse gases (GHG) emitted (IDEAM et al., 2018) in 2014.

Savings in this sector are expected to be achieved through the implementation of several programs such as replacement of incandescent bulbs, inefficient refrigerators, air conditioning, and other appliance; the implementation of efficient burners, designs, and construction for sustainable housing; and the substitution of the firewood in the rural and marginal areas with liquefied petroleum gas (LPG) (UPME, 2010).

Nevertheless, the effectiveness of such kinds of programs may face two particular barriers, a low demand for efficient equipment and a less than expected effectiveness (Belaïd et al., 2018). Efficient equipment requires investment that low-income household groups cannot afford since 82% of the total residential sector is represented by low-income groups (SUI, 2018). This situation forces the government to consider subsidies so these groups can buy new efficient equipment. The less expected effectiveness may be due to the bad quality of energy

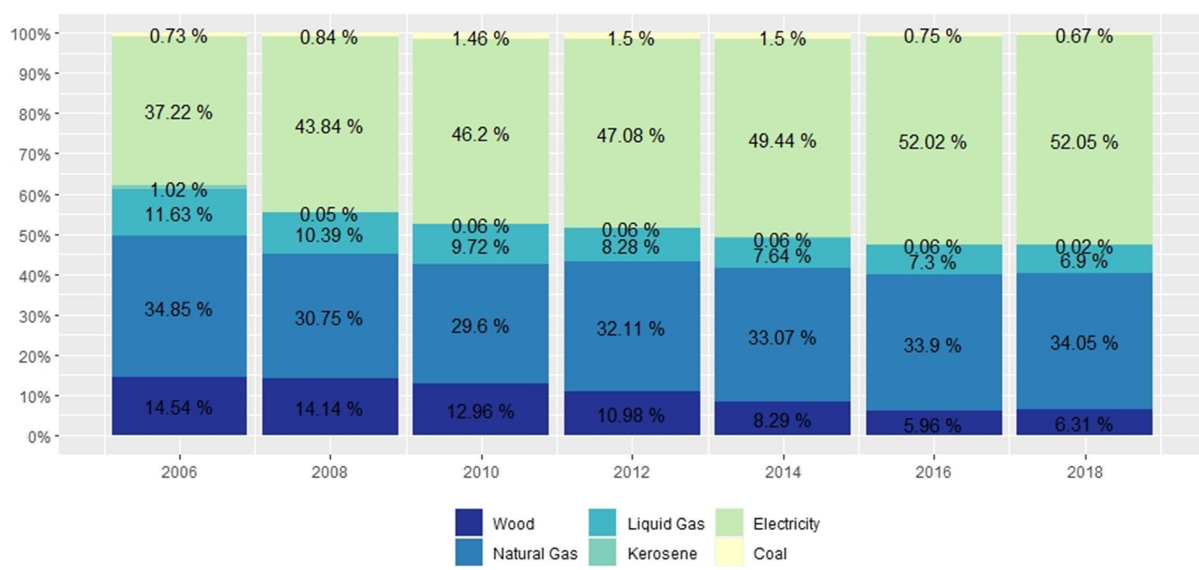

Fig. 1 Amount of energy sources consumed in the Colombian residential sector (urban areas). Source: Energy Mining Planning Unit (UPME, 2019)

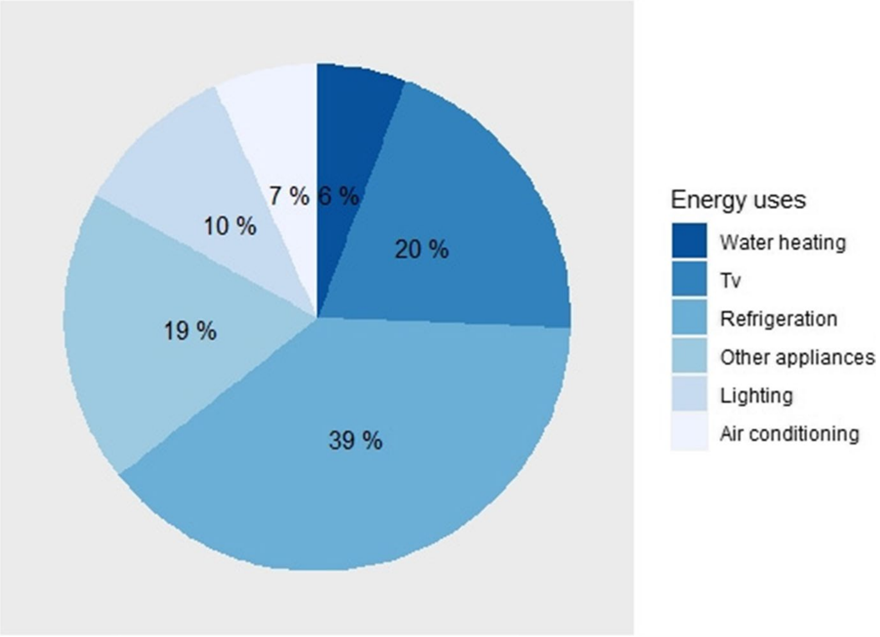

Fig. 2 Colombian electricity consumption by the urban residential sector and destination uses in 2015. Others refer to services like ironing and washing. Source: Energy Mining Planning Unit (UPME, 2016a)

retrofits, errors in measuring energy efficiency, and the rebound effect (RE). In this paper, we focused on studying the direct rebound impact (Belaïd et al., 2018).

The rebound effect is a widely accepted phenomenon introduced by Stanley Jevons in the late nineteenth century (1865) and popularized in the last decades by Khazzoom (1980) and Brookes (1990). An interesting debate about this topic can be found in Berkhout et al. (2000), and Musters (1995). Generally speaking, the RE states that a change in the technical efficiency of an energy service can change the overall consumption pattern of this service, due to the behavioral responses of economic variables such as income, price, financial gains, product costs, and material substitution (Font Vivanco & Voet, 2014). Similar definitions of the RE can be found in the literature (Berkhout et al., 2000; Binswanger, 2001; Brookes, 1990; Girod et al., 2010; Greening et al., 2000; Sorrell & Dimitropoulos, 2007; Sorrell et al., 2009; Weidema, 2008). Recently, the RE has reached the interest of an important number of academic, public, and private entities due to the fact that it can negatively affect the possible environmental savings planned through sustainable production policies and technologies (Maxwell et al., 2011). Some examples of these policies are the United Nations Environment Programme (UNEP), the International Energy Agency (IEA), the European Commission (EC), and the European Environment Agency (EEA), among others (Font Vivanco et al., 2016).

Thus, the main research question addressed here is "which role the rebound effect plays in the developing Latin American economy?" Thereby, the goal of this study is to empirically measure the direct RE for all the household services consuming electricity in Colombia by analyzing panel data generated at 15 different states from 2005 to 2013. Although there are several studies about the direct RE for country members of the Organization for Economic Co-operation and Development (OECD) and for developed countries, these studies unlikely represent the situations of developing countries where empirical measures of this phenomenon are scarce. That is why, this study starts filling the gaps observed around this topic in Latin American economies, by providing novel insights about the direct RE in Colombia, since its value has been historically theorized rather than empirically tested. The literature suggests that the RE varies by region and that it is lower than in developing countries due to an unsaturated demand for energy services (Font Vivanco & Voet, 2014; Lu & Wang, 2016; Sorrell et al., 2009; Thomas & Azevedo, 2013; van den Bergh, 2011; Yu et al., 2013). We aimed to test these statements since there is limited empirical evidence of them (Yu et al., 2013).

Our study is relevant to various stakeholders: government, non-government agencies, policymakers, and academics which can gain knowledge on the role of the rebound effect in achieving sustainability goals, whereas practitioners can gain insights into the role of the rebound effect in Latin American economies. The content of this paper is organized as follows. The "Theoretical aspect and literature review" section provides the rebound effect foundations and a literature review of the RE of electricity consumption in developing countries. The "Model and data acquisition" section presents the model and data applied. The "Results" section provides the results found in this study, whereas the "Discussion" section presents their associated discussion. Finally, the "Conclusions and policy implications" section provides conclusions and final remarks.

Theoretical aspect and literature review

This section presents a short description of the direct RE and a literature review of the RE of electricity consumption in developing countries.

Rebound effect

Three types of rebound effect can be distinguished: (1) direct effect, (2) indirect effect, (3) economy-wide effect (Greening et al., 2000). The direct effects are related to the change in consumption or production of a single energy service, e.g., electricity. The indirect effects are associated with changes in consumption for other goods and services apart from the improved energy service. Both of these phenomena are considered microeconomic effects. The economy-wide effects represent the effect on the macroeconomics and are the result of the joined direct and indirect effects. Direct effects are the most studied ones due to the lack of tools and the difficulty to measure the other types of rebound, which associate patterns of consumption and macroeconomics (Font Vivanco & Voet, 2014).

The direct RE has been extensively measured through two main approaches: quasi-experimental approach based on measures before and after the implementation of energy efficiency improvements, and econometric approaches (Sorrell et al., 2009). The quasi-experimental approach is rare due to the requirement of a high amount of data, typically collected by surveys (Freire-González, 2011; Haas & Biermayr, 2000). This approach is prone to bias due to the methodological approach. Commonly, the studies present simple before-after comparisons, without the use of a control group or explicitly controlling for confounding variables. Moreover, the size of the samples is small and is not randomly selected (selection bias), the error associated with the estimates is not provided, and in many cases, the monitoring periods are too short to capture long-term effects (Sorrell et al., 2009). Alternatively, the econometric approach proxies the RE through the elasticity price of the energy services under study, by using secondary data at different level of aggregation, e.g., household, region, country, and forms e.g. panel data, time series, and cross-sectional analysis (Belaïd et al., 2018; Sorrell et al., 2009). Moreover, by using econometric approaches, it is possible to conduct elasticities estimations on the short term (also knowns as short run), where the stock of production factors is assumed to be fixed, as well as long run (also knowns as long term) where it is variable (Sorrell et al., 2009). The rebound effect can be simply measured by Eq. (1)

$$\text{Rebound effect}(\%) = 100 \times \frac{\text{expecting savings} - \text{actual savings}}{\text{expecting savings}} \tag{1}$$

Particularly, a rebound effect of 0% means full achievement of energy reduction, while a 100% means complete failure. Values greater than 100% mean that the energy efficiency improvements increase the overall amount of energy use, a phenomenon known as the "backfire effect" (Sang-Hyeon, 2007).

Under certain circumstances, the direct RE can be studied using the econometric approach through efficiency measures of the energy services (Berkhout et al., 2000; Khazzoom, 1980; Sorrell, 2007; Sorrell & Dimitropoulos, 2007) as:

$$\eta_\varepsilon(E) = \eta_\varepsilon(S) - 1 \tag{2}$$

where $\eta_\varepsilon(E)$ represents the efficiency elasticity of the demand for energy and $\eta_\varepsilon(s)$ is the energy efficiency elasticity of the demand for useful work on an energy service. When $\eta_\varepsilon(s) = 0$, there is no direct rebound effect. When $\eta_\varepsilon(s) > 0, \eta_\varepsilon(E) < 1$ and there is a positive direct rebound effect. Finally, a $\eta_\varepsilon(s) > 1$ means that the demand is elastic and there exists "backfire" (Saunders, 1992). Due to the difficulty to measure ε, the direct RE is mainly approached by the price elasticity of energy demand as follows (Berkhout et al., 2000; Sorrell, 2007; Sorrell & Dimitropoulos, 2007).

$$\eta_{\varepsilon}(E) = -\eta_{p_E}(E) - 1 \quad (3)$$

where η_{p_E}(E) represents the price elasticity of the energy demand. This alternative is prone to overestimate the real value of the RE though it is more available than preferred measures to approach the RE such as the energy cost elasticity of the demand for useful work $\eta_{p_S}(S)$ or the energy cost elasticity of the demand for energy $\eta_{p_E}(S)$ (see Sorrel and Dimitropoulos (2007) for detailed definition and limitations of the different variables used to estimate the RE). Moreover, Eq. (3) is based on symmetry and exogeneity assumptions. Symmetry implies that consumers respond in the same way to energy price decline and energy efficiency improvement, whereas exogeneity implies that energy prices change cannot affect energy efficiency (Z. Wang et al., 2014).

Additionally, the price elasticity of the energy is in accordance with Haas and Biermayr (2000) traditional estimated by the following function of demand:

$$Ln\left(E_t\right) = C + \beta_1 LnP_t + \beta_2 LnY_t + e_t \quad (4)$$

where C is a constant, $\beta1$–$\beta2$ are the parameters to be estimated, with $\beta1 = \eta_{p_E}(E)$, and e_t represents the random error term. E_t is the energy demand, P_t the energy price, and Y_t the income variable. T represents the time scope.

Literature review of the rebound effect of electricity consumption in developing countries

The literature suggests that the RE may be higher in developing countries due to the unsaturated demand for energy services (Font Vivanco & Voet, 2014; Lu & Wang, 2016; Sorrell et al., 2009; Thomas & Azevedo, 2013; van den Bergh, 2011; Yu et al., 2013). According to van den Berg (2011), the magnitude of the RE is higher in developing countries than in developed ones for several reasons. First, developing countries often show a higher growth rate than developed countries, retaining higher potential for increased energy-intensive consumption. Second, the cost of energy in developing countries is relatively higher than that in developed countries. Third, developing countries are far from saturation in their consumption of essential energy services such as lighting. Fourth, developing countries may "technologically leap-frog" in terms of energy-efficient technologies as well as new energy-using devices. Fifth, lower education and less availability of information in developing countries possibly contribute to decision-making by firms, households, and governments that do not take all relevant economic and associated energy use effects into account at the time to establish public policies.

Empirical evidence of the direct RE for energy services consuming electricity in households among developing countries has focused on countries from Asia and Africa (see Table 1). The value of the RE varies significantly depending on the region, the level of income, and the method applied to test it. Zhang and Peng (2017) applied a panel threshold for the timespan 2000–2013 and suggested that the direct RE for the low-income household level in China is 68%, whereas for the high-income households level, this effect was estimated to be 55%. Across regions (provinces), Wang et al. (2014) used panel data with 30 provinces of China along the period 1996–2010, suggesting that the direct RE ranges 72% (short term) and 74% (long term).

Measurements for the direct and indirect RE in China suggest that this phenomenon is significantly higher than the indirect rebound RE. Lu and Wang (2016) applied an energy input–output data (EIO) and scenarios simulation to study the direct plus indirect rebound effect in China with provincial panel data from 1996 to 2010. Their results indicate that the direct plus indirect partial rebound effect is 79% (long term) and 78% (short term) from which the direct effect is 72% in the long term and 74% in the short term. Similarly, Wang et al. (2016) applied similar models for estimating a direct and indirect RE in Beijing for the period 1990–2013 suggesting that the direct RE is 40% (long term) and 15% (short term), whereas the indirect RE in the short term ranged from 8 to 21%, and the long-term effect ranged from 6 to 15%. Their results imply that efficiency improvements in residential electricity use had little effect on the implicit energy consumption associated with other goods and services in Beijing.

Alternatively, Sang-Hyeon (2007) found that the direct RE in south Korea ranged 38% (short term)

Table 1 Studies in developing countries related to the electricity residential consumption

Author	Country	Rebound effect	Magnitude %	Method
Sang-Hyeon (2007)	South Korea	Direct	38 short term 30 long term	Price elasticity
Freire-González (2010)	Spain	Direct	35 short term 49 long term	Price elasticity
Fox and Hara (2012)	US	Direct	8 long term	Price elasticity
Wang et al. (2014)	China	Direct	72 short term 74 long term	Price elasticity
Lu and Wang (2016)	China	Direct plus indirect	78 short term 79 long term	Price elasticity and energy input–output data
Wang et al. (2016)	Beijing, China	Direct and indirect	16 direct short term 40 direct long term 8–21 indirect short term 6–15 indirect long term	Price elasticity and energy input–output data
Zhang and Peng (2017)	China	Direct	72 long term	Price elasticity
Labidi and Abdessalem (2018)	Tunisia	Direct	81 long term	Price elasticity
Alvi et al. (2018)	Pakistan	Direct	42.9 short term 69.5 long term	Price elasticity
Su (2018)	Taiwan	Direct	33 long term	Surveys

and 30% (long term) during the period 1975–2005 and provided a direct RE estimation via surveys for air conditioners between 57 and 70%. Also, Alvi et al. (2018) used the time series data from 1973 to 2016 generated in Pakistan and suggested a RE around 43% (short term) and 70% (long term).

Labidi and Abdessalem (2018) provide the only study that empirically measures the direct RE for an African country (Tunisia). Using a balanced panel data set for a sample of 21 cities in Tunisia over the period 1995, 2000, 2005, and 2010, the authors provided the highest measure of the studies reviewed (RE = 81%). Moreover, they argued that the direct RE could be reduced to 71.9% if the subsidy granted for the residential electricity consumption is removed by the state.

Results provided by Su (2018) in Taiwan are significantly valuable given the fact that the author measures the RE through a survey rather than through aggregate data. In this case, measures are provided by different energy services such as air conditioner (72%), lightning (11%), TV (3%), and refrigeration (70%). Its study was carried on via surveys with 7677 household data between the period 2014 and 2017. Moreover, the author suggests an average of 33% RE for all appliances consuming electricity.

Finally, Fox and Hara (2012) found a direct RE in the USA of 8%, whereas Freire-González (2010) estimated a direct rebound effect of 35% in the short term, and 49% in the long term in Catalonia Spain.

Literature review points out two critical outstanding research gaps. First, existing studies show that the rebound effect is significantly higher (RE > 30%) in developing than in developed countries (RE < 30%). Second, studies also show that measures in Latin American economies have been systematically omitted, mainly because the data required to conduct such studies are not available and have poor quality (Economic Consulting Associates, 2014; Sorrell & Dimitropoulos, 2007). These findings support the motivations of this study.

Model and data acquisition

This section presents the econometric model and the variables used to estimate the RE of all the energy services consuming electricity in the Colombian household sector.

Econometric model

This paper estimates the long-term RE through econometric approaches. Thus, the following model is applied:

$$Ln(E_{it}) = \alpha + \beta_1 LnEP_{it} + \beta_2 LnGP_{it} + \beta_3 LnGDP_{it} + u_{it} \quad (4)$$

where α is a constant, $\beta1$–$\beta3$ are the parameters to be estimated, with $\beta1 = \eta_{p_E}(E)$, and u_{it} represents the random error term. E_{it} is the explanatory variable and represents the electricity consumption in GWh per habitant (number of households with electricity services) in the state i and period t of the households. EP_{it} represents the price of electricity in the state i and period t. We calculate EP as a weighted average price for each year between the electricity price for the different household income levels. GP_{it} is the price of the household gas, as a substitute good, in the state i and period t. GDP_{it} represents the income variable per capita (number of households with electricity services) measured for the gross domestic product GDP divided by the number of households with electricity service in the state i and period t. This variable is selected as an estimation of the household income since the desegregated data for the income variable, provided by the official entity in charge, is in terms of GDP as a whole.

Additionally, and given the fact that the consumption of electricity is strongly positively correlated with the winter or summer seasons, plenty of studies include a climatic variable in their analysis. Several authors included the heating degree days HDD and/or the cooling degree days CDD as explanatory variables (Alvi et al., 2018; Freire-González, 2010; Haas & Biermayr, 2000; Hartman, 1988; Labidi & Abdessalem, 2018; Lu & Wang, 2016; Sang-Hyeon, 2007; Z. Wang et al., 2014; Zhang & Peng, 2017). Those studies have been conducted in countries of Europe and Asia that have seasonal temperatures. This implies that they experience extreme temperatures during the summer and winter, and therefore, the consumption for calefaction or refrigeration raises the electricity consumption. In this study, the variable heating degree days (HDD_{it}) (base: 18 °C) of Colombia in period t and state i has been included to account for the climatic variable; however, the statistical test suggested that the climatic variable is not significant for the Colombian case (see supporting information S1 for results of the model with HDD_{it} variable). Therefore, the climatic variable was removed from the final econometric model. This meanly because Colombia is located in the tropic region and it does not have seasons. Then, the temperature does not change significantly over the year.

It is worth mentioning that different models were developed in order to find the most suitable model for the analysis. A model without the variable GP and others with the GDP variable gross domestic product without any conversion were tested. Both models result in less significance (see supporting information S2).

To determine which regression model applied (random effects, fixed effects, or pooled regression), we follow Granados's (2011) procedure. We use fixed effects because the null hypothesis of both Breusch-Pagan and Hausman was rejected, indicating that there exist un-observable components associated with each department and there are systematic differences between the estimators (fixed and random). For a detailed description of the procedure, see the supporting information S3.

Data collection

Colombia counts with 33 states including the capital city (Bogotá). Information for all the variables mentioned above was collected for all the states from 2005 to 2017. However, and due to the lack of information and accuracy for some states, a sample of 15 states (Antioquia, Atlántico, Bogotá, Bolivar, Boyacá, Caldas, Cundinamarca, Cordoba, Huila, Magdalena, Meta, Risaralda, Santander, Tolima, and Valle del Cauca) was finally selected for the period 2005–2013. These states accounts for 56% of the gross domestic product and 80% of the total housing units in 2013 (DANE, 2018a, 2018b).

Data of the total household gas and electricity consumption, the number of households, and price of natural gas and electricity was obtained for every year and state under study from the superintendence of domiciliary public services (SUI by his acronym in Spanish) (SUI, 2018) see supporting information S4 for descriptive analysis for the number of households with electricity services and price by income level). Data on the income was obtained from the National Administrative Department of Statistics (DANE by his acronym in Spanish) (DANE, 2018b); all the monetary variables are in constant price from 2005 and were collected for every year and state under study. The time period of the data is annually. Table 2 presents some descriptive statistics for the sample.

Results

Results for the RE at the national level were estimated using a random effects model. The panel data regression suggests that the direct RE for all household energy services consuming electricity is 83.4% (see Table 3). Thus, only 16.6% of the potential savings are achieved. Except for GDP, all the variables were significant at 90% or higher confidence level.

To estimate price elasticities by states, we use the random-effects model with dummy variables for each of them, although the Breusch-Pagan test suggested not to reject the null hypothesis that is $Var(v_i) = 0$. However, pooled regression estimates were equal to random effects ones (supporting information S5). Since it was not possible to estimate the slope interactions by states using the pooled model, we apply a random-effects model to account for such effects. Due to the perfect collinearity found in this model, the natural log of energy price was omitted, then the estimation shows the state-rebound effect for every cross-section unit.

The results suggest that the direct RE for all household energy services consuming electricity in the long term is present for all the states but in different ranges. We found values from 64.7% in Atlantico to 78.9% Meta (see Table 4). Almost all the variables are significant at 90% of confidence except the log of GP and the states of Atlantico, Cordoba, and Magdalena.

Table 2 Descriptive statistics of the variables analyzed for 15 states in Colombia, 2005–2013

Variable	Mean	Std. Dev	Min	Max
E	923.178	868.083	0.966	3,280.433
EP	384.934	98.953	217.026	576.969
GP	910.87	329.241	303.7163	2,2112.558
GDP	0.152	1.237	0.015	14.401

E electricity consumption per subscriber of electricity services, *EP* electricity price, *GP* gas price, *GDP* gross domestic product per subscriber of electricity. All variables 2005 current prices. Source: author's calculus

Table 3 Random effects model: total electricity demand in households 2005–2013. Panel of 15 states of Colombia. Generalized least squares (GLS) estimation (cross-section weights). $N = 135$

Variable	Coefficient	*z*-statistics	Prob
α	−6.3437	−6.14	0.000**
lnEP	−0.8345	−3.16	0.002
lnGP	0.5539	2.8	0.005
lnGDP	−0.3368	−4.42	0
Adjusted *R*-squared			
Within	0.0871		
Between	0.5673		
Overall	0.2371		
Wald chi^2	29.36		0.0000***

Signif. codes: *** at 1%, ** at 5%, *a t 10%

Table 4 Random effects model: total electricity demand in households 2005–2013. Generalized least squares (GLS) estimation (cross-section weights) with interactions between state dummy variables and log of energy consumption. Yearly data for 15 states. $N = 135$

Variable	Coefficient	*z*-statistics	Prob
lnGP	0.551	1.64	0.103
lnGDP	−0.270	−2.96	0.004**
lnEP_Antioquia	−0.742	−1.74	0.084*
lnEP_Atlantico	−0.647	−1.51	0.133
lnEP_Bogotá	−0.732	−1.72	0.088*
lnEP_Bolivar	−0.783	−1.83	0.07*
lnEP_Boyacá	−0.706	−1.83	0.069*
lnEP_Caldas	−0.749	−1.89	0.061*
lnEP_Cundinamarca	−0.725	−1.76	0.081*
lnEP_Córdoba	−0.710	−1.65	0.101
lnEP_Huila	−0.786	−1.83	0.07*
lnP_Magdalena	−0.659	−1.54	0.125
lnP_Meta	−0.789	−1.91	0.058*
lnP_Risaralda	−0.738	−1.84	0.068*
lnP_Santander	−0.775	−1.86	0.065*
lnP_Tolima	−0.783	−1.91	0.058*
lnP_Valle_del_Cauca	−0.718	−1.72	0.089*
α	−6.694	−6.42	0.000***
Adjusted *R*-squared	0.3025		
F-Statistic	4.42		
prob-F	0.000		
Root MSE	0.51565		

Signif. codes: *** at 1%, ** at 5%, *at 10%

Discussion

Results for the direct RE at the national level are slightly higher (83.4%) compared with existing studies for developing countries (see Table 1). RE in Colombia appears to follow a geographic pattern, with higher values in those states located at the interior of the country (Meta, Huila, and Tolima), whereas low values (Atlántico, Magdalena, and Cordoba) were observed for those states located on the coast of the country. The reason for such patters is a high demand for electricity on the coast where the yearly average temperature is above 28° (NOAA & AA, 2017); thus, the high amount of electricity is associated with the demand for additional energy services for refrigeration and air conditioning. These services are not needed or are consumed in smaller quantities in the center of the country, leading to saturated energy consumption on the coast. In 2013, the monthly amount of electricity consumed by household in the coast was 239.12 kWh (Atlántico), 216.62 kWh (Magdalena), and 182.14 kWh (Cordoba). At the interior of the country, the consumption was 130.94 kWh (Meta), 118.58 kWh (Huila), and 100.26 kWh (Tolima) (DANE, 2018a; SUI, 2018).

The difference between the result at the national level (83.4%) and at the state level (64.7–78.9%) may be explained by the level of aggregation (Birol & Keppler, 2000). Similar results were observed between the national and regional levels for the long-term RE for road freight transport in China. Wang and Lu (2014) estimated a long-term RE of 84% at the national level, whereas for three different regions (eastern, central, and western), the magnitude of the RE ranges from 52 to 80%. It is worth noting that results at national and state, other than at the regional level for the RE of residential electricity consumption, were not found in the literature; therefore, more adequate comparisons were not possible.

In our model and different from the studies reviewed (see Table 1), the coefficient of the variable GDP is negative; this may be explained by the particular conditions of the Colombian electricity sector. The household sector in Colombia is stratified into six levels according to socioeconomic state and income. While levels one to three are considered low income, levels four, five, and six jointly are labeled as middle and high income, respectively. Such disaggregation plays an important role in residential electricity consumption given the existence of a scheme of subsidies for the final price to pay for electricity. Particularly, there is a mixed subsidy system where the high-income levels and the commercial consumers pay an additional fee (contributions) on the price of electricity (20% of the price) to subsidize the low-income levels (cross-subsidy). Additionally, the government subsidizes a portion (direct subsidy) when the contributions are not enough (CREG, 1997a). This fact becomes significant given that low-income households account for 80% of residential electricity consumption in Colombia (SUI, 2018) and receive up to 60% of subsidies in the price of the electricity (CREG, 1997b). However, it is highlighted the coefficient of GDP was not significant in our model, which suggests that more research is needed to make significant conclusions.

Compared with existing studies, the contrasting results found here have several explanations: (i) the data processed, (ii) the method applied, and (iii) the particularities of each country. Regarding the data and method applied, our study used panel data at the state level for 9 years (2005–2013), whereas other authors include a large timespan. Sang-Hyeon (2007) included data for thirty years (1975–2005). Wang et al. (2014) evaluated four years (1996–2010) of a provincial data set in China, whereas Alvi et al. (2018) used aggregate data with 43 years (1973–2016) in Pakistan. The above authors applied the method developed by Hass and Biermayr (2000) and Dargay and Gately (1997) to tackle the assumption of symmetry (demand responds in the same way as the energy price and energy service price declines or increases) imposed in the theoretical framework (see the "Model and data acquisition" section). Specifically, the method decomposes the price of the electricity into three different components, Pmax (the highest price in history), Pcut (prices fall), and Prec (price recovery) from which the Pcut stands for the direct RE. In this way, only the factors affecting the energy price drop are taken into account and overestimations are avoided.

Another important difference is the type of data applied, while the above studies use panel data for different states or provinces, Zhang and Peng (2017) used data for 13 years (2000–2013) for income level (low, middle, and high). Particularly, Labidi and Abdessalem (2018) used a balanced panel data set for a sample of 21 cities in Tunisia over the period 1995, 2000, 2005, and 2010 and studied the rebound effect in two cases (with subsidies and without subsidies of the government for the electricity).

Regarding the variables included in the econometric models, it is noted that the studies reviewed commonly include a variable accounting for a substitute good (in this case natural gas) and a climatic variable into their analysis, since the consumption of electricity is strongly positively correlated with the winter or summer seasons. In the case of the Colombia household sector, natural gas is used as a substitute for electricity mainly for cooking and in less proportion for water heating (see the "Introduction" section) (UPME, 2016a). The significance of these variables in our models (see Tables 3 and 4) suggests that natural gas is positively correlated with the consumption of electricity, which means that the consumption of electricity increase once the price of the natural gas increase. A similar procedure is applied by Freire-Gonzáles (2010) but natural gas was excluded from the final models given his non-significance.

Moreover, several authors (see Table 1) applied an error correction model (ECM) to capture the effect of the RE in the short term. Yet, in these models, all the variables should be non-stationary in order to perform correctly. In our study, these pre-conditions are not satisfied by all the variables (see supporting information S6), then the ECM cannot be performed since the variables are not co-integrated (they do not share a common stochastic path). The reason for such results may be explained by the small number of periods included in this study 2005–2013 (9 years).

Limitations of our study to be addressed in the future include (i) the quality of the data obtained from national datasets has several gaps, especially for the information accounting for the number of households with electricity services; for some states, such data was available only along the period 2005–2013. Furthermore, when the data was available, there were gaps in the information. Thus, the number of households with electricity services for all the income has missing values. (ii) Due to the lack of information for such a level of desegregation, the household income variable had to be calculated as gross domestic product divided by the number of households with electricity services. More desegregated information for GDP in Colombia can be found for GDP/per capita, implying that this variable may add uncertainties to the results. (iii) The price of the electricity was estimated as a weighted average of the price of electricity for each household income level (Colombian electricity regulated market has six different prices for the electricity depending on the income levels). Low-income levels have a subsidy of up to 60% in the electricity price to pay. In contrast, the high-income levels have to pay a 20% extra contribution to the electricity cost (CREG, 1997b). Information to differentiate the price of the electricity without the number of subsidies and contributions was not possible to find.

Furthermore, uncertainties included by the assumptions of symmetry and exogeneity may be present in the study. Authors like Hass and Biermayr (2000) and Dargay and Gately (1997) have cited the assumption of symmetry, as a matter of interest when studying the rebound effect. In our study, a model with a price decomposition was build up but the result was not significant (see supporting information S7 for model with price decomposition). Reasons for such results may be attributable to the quantity and quality limitations discussed above. Other sources of uncertainties come from (i) the relationship between the rebound effect and the costs of capital (Freire-González, 2010). It would be necessary to estimate the indirect and economy-wide effects to obtain the total magnitude of energy efficiency improvements in households. It is worth noting that the direct and indirect REs are likely to be inversely proportional. A large direct RE (e.g., this study) implies that an important part of the savings will be re-spending in additional electricity consumption leaving less income to be re-spending in others services and (ii) the correlation between rising energy prices and investments in energy efficiency. Preferred measures of the direct rebound effect may include efficiency elasticities, energy service price elasticities, and energy price elasticities, in searching for controlling self-selection of efficient appliance purchase (Thomas & Azevedo, 2013); such measures become significant when the rebound effect is estimated through hybrid methods (direct + indirect rebound effect) (L. Wang et al., 2019).

The combination of both limitations and uncertainties may bias the results. Therefore, it is worth mentioning that the R^2 obtained in the general model (see Table 3) indicates that the variables included in the model explain only 9% of the electricity consumption, contrary to similar studies (see Table 1) where variables such as electricity price, GPD, and population (here as the number of households with electricity services) explain more than 80% of the electricity consumption. Such differences may be attributed to (i) the quality of the data (discussed above) and (ii) the omission of variables that could be related to the electricity consumption, such as rates of ownership of electrical appliances, number of persons per household, and age of the members in the families, among others (Su, 2018). Additionally, the variability associated with the variable number of households with electricity services may affect the results. High variability across the years and income level was found for some states: Risaralda (between 15 and 155%) and Santander (14 and 176%), whereas low values of variability are presented in the states of Antioquia (between 2 and 17%) and Bogota (between 3 and 9%), where two of the most important cities (Medellin and Bogota, respectively) are located; the states of Cordoba and Huila follow similar patterns of variability (see supplementary information S4.1).

Future research aims at different areas should cover efforts to improve the quality of the data and to insulate the effect of the subsidies and contribution from the electricity price. Furthermore, efforts should be made to study the direct rebound effect of residential electricity consumption at different levels of desegregation, as the RE change significantly depending on the level of income or the region. Results of this study suggest that the rebound effect follows a geographic pattern, yet the causes of such patters need to be studied. Future research should focus on studying the rebound effect at regional and city levels. Moreover, studying the rebound effect by income levels may reveal different patterns, particularly attributed to the fact that 80% of the Colombian population belongs to the low-income level. Finally, studies of different energy services, e.g., transport, should be encouraged mainly because the transport sector is responsible for around 12% of the GHG emissions in Colombia (IDEAM et al., 2016). Then, efficiency policies that seek to reduce such values may not be achieved for the effect of the rebound effect.

Conclusions and policy implications

The RE has been extensively studied in the last decades in developed countries for several energy services such as transport, household heating and cooling, and electricity (Sorrell et al., 2009). Measures for the RE in developing countries have been systematically omitted from the literature and estimations are assumed rather than empirically measured. In this sense, this paper empirically estimates the direct rebound effect for all household energy services consuming electricity in Colombia, through panel data of 15 states over the period 2005–2013. The results obtained indicate the existence of a direct rebound of 83.4% for the long term, supporting the hypothesis that the rebound effect may be more significant in developing than in developed countries.

The RE has several implications for policymakers given the fact that it can undermine the environmental savings planned through sustainable production policies and technologies (Maxwell et al., 2011). In this regard, the results show that the RE for electricity consumption in the Colombian household sector has a non-negligible value, which implies that a drop of 1% in the price of electricity will increase the demand by 0.834%. This result is significantly important for the Colombian government due to the high number of resources that are planning to be invested in efficiency improvements for the production and consumption of electricity. Concretely, electricity efforts have been put into strategies for consumption improvements such as the replacement of refrigerators and LED bulbs. Then, not considering the rebound effect may reduce the effectiveness of such energy and environmental policies.

Furthermore, it should be noticed that the potential savings gained by the above strategies are likely to be spent not only on energy services that are close to saturation such as lighting or refrigeration, but also on water heating, air conditioning, and other services such as the internet. Additionally, income effects (indirect rebound effects) arising from such strategies should be taken into account since the indirect energy requirements of households are bigger than the direct energy requirements (Dimitropoulos, 2007). Such additional consumptions may increase the productivity of the country alongside the energy demand. Moreover, understanding the environmental impacts (environmental rebound effect) associated with the additional consumption of energy (both direct and indirect rebound effects) will provide a better perspective on the real implications of such efficiency improvements on the economy (Vélez-Henao et al., 2020).

The Colombian government is encouraged to account for the importance of the rebound effect and develop instruments to control it in order to achieve the commitments made in the COP 21 and the national efficiency targets. Some useful mechanisms to do it may be including economic instruments, e.g., taxes and programs and campaigns, for the efficient use and saving of energy. Particularly, the last one has proven to have positive and significant impacts on the consumption of electricity, e.g., the "Apagar Paga" campaign launched by the government to reduce energy consumption through economic incentives, which also encouraged savings and penalizes additional consumption based on the average electricity consumption of the houses in the household sector. This example represents efforts that were translated into a significant reduction in the growth of consumption, a key factor to avoid given the emergency caused by the El Niño phenomenon in 2016–2017.

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Declarations

Conflict of interest The authors declare no competing interests.

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