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Understanding dynamics and policy for renewable energy diffusion in Colombia

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ABSTRACT

Colombia has committed to reduce greenhouse gas emissions in 20% by 2030 with respect to business-as-usual in the COP21. One policy is the Renewable Energy (RE) law launched in 2014, aiming “to promote the development and use of non-conventional energy sources” with indirect incentives, such as tax reduction or exemptions. Direct incentives, such as price-based, are not included in the law. Experiences in other countries have proven that direct incentives are more efficient than indirect ones to promote RE. The purpose of this study was to evaluate incentives for RE diffusion in Colombia through a simulation model for energy policy recommendations. We tested four incentives: tax reduction, feed-in-tariffs, tradable certificates, and technical subsidies; and four RE sources: small hydro, biomass, wind, solar and geothermal. Simulation results show that a combined scenario using feed-in-tariffs and technical subsidies can boost the deployment of RE, avoiding significant price increases for the final consumer. None of the incentives leads to reaching the RE target, given the growing demand for energy. Complementary policies could focus on improving energy efficiency.

1. Introduction

Reducing emissions and the carbon footprint has become a priority worldwide. Renewable energy (RE) sources have become an obligation rather than an option [1]. Latin America has a current population of over 500 million, with a growing population trend that implies an increase in energy demand. Given this increase, along with climate change concerns and energy security issues, the International Energy Agency (IEA) expects that the development of RE will take off, especially in developing countries [2].

Efforts to promote RE have been expanding in recent years. RE generation should now increase from 23% today to more than 50% by 2050, in order to maintain the global average temperature within the desired ranges [3]. RE development has been centralized in Europe and North America, while Asia and Latin America have the largest unexploited potentials (80% and 74%, respectively) [4]. By contrast, the share of thermoelectric plants has increased in the last decades in countries like Brazil, Argentina, Colombia and Chile [5]. Reasons for this include the high cost of RE technologies that cannot compete with traditional generation, as well as the intermittency and uncertainty of the generation which have become a risk factor for investors [6].

In addition to the challenge of mitigating climate change, Colombia must diversify its energy mix and supply electricity to non-connected areas.[1] Historically, the Colombian electricity sector has depended on traditional sources. In the early 90s the country faced a major energy crisis due to dependency on large hydro (more than 80% at that time), mismanagement of the energy market and one of the strongest El Niño on record [7]. Current total installed capacity has 67% hydro, 27% thermal energy, and 6% minor plants, with capacities below 20 MW [8]. The recent event of El Niño in 2015–2016 served to expose the vulnerability of the system. During this phenomenon, the government was forced to implement an

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[1] Non-connected areas in Colombia are defined as all municipalities, towns and villages that are not connected to the national grid and do not have viable conditions for interconnection [56]. This area corresponds to 4.4% of the total population (about 2 million people).

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energy saving campaign in order to avoid some expected power outages.

The Colombian government has formulated different incentives for RE promotion. The first mechanism introduced in 2002 consisted of an income tax exemption for RE for wind and biomass [9]. The government then introduced the Renewable Energy Law (Law 1715/2014), which seeks to formulate several incentives to promote RE and self-generation in the country [10]. Although the regulatory policies to support the law have not been fully established [11], policymakers, the energy sector, government actors and academics should analyze the effects of different incentives and anticipate the possible impacts of the law on the energy system. Most studies in Colombia have focused on one technology only, such as wind [12] or solar energy [13,14], while more extensive studies including other technologies were developed before the RE law was introduced [15].

This paper presents a simulation model as a tool for evaluating the impact of new incentives on the deployment of RE in Colombia. We present the status of RE in Colombia in section 2 accordingly. Section 3 reviews existing diffusion models in Colombia and worldwide, and describes our proposed model based on system dynamics. The simulation of different incentive scenarios is shown in section 4, while conclusions are stated in section 5.

2. Renewable energy in Colombia

Colombia has the second largest potential for hydropower in Latin America, after Brazil [16], with a potential of 5 GW for small hydropower (SHP) in the feasibility phase[2], taking into account social and environmental constraints [17]. Colombia also has conditions for wind and solar energy, some areas have a wind density of over 400 W/m^2, while the average radiation of the country in the National Interconnected System (SIN from its name in Spanish) is around 4.5 kWh/m^2 [18], and the potential of Colombian radiation in non-interconnected areas reaches 6 kW h/m2 [19]. Moreover, the country's agricultural sector, which includes coffee and sugar cane plantations, has biomass and cogeneration potential. We present the status of RE in Colombia for SHP, biomass, wind, solar utilities and geothermal in Table A1 of the Appendix; the values reported in the Appendix also constitute an input for the simulation of scenarios. Although Colombia has the potential for different ocean technologies, we exclude these from our study given that such technologies are on the preliminary stages in the country [20].

The Colombian government introduced Law 1715 (Renewable Energy, or RE Law) in May of 2014. This law aims "to promote the development and use of non-conventional energy sources, mainly renewable, in the national energy system, by integrating them into the electric market, non-connected areas and other energy uses" [10]. The law also establishes the RE sources for Colombia: biomass, ocean, small hydropower, wind, geothermal and solar energy. The RE law specifically formulates four indirect incentives, all related to tax reductions or exemptions: a 50% income tax reduction, a VAT tax exemption, an import duties exemption and accelerated depreciation (Decree 2143/2015) [21]. Additionally, the government declared an increase of 0.01 cUSD/kWh in the electricity tariff designed to subsidize the fund for non-conventional energy and efficient energy management within the RE law (referred to by its Spanish acronym FENOGE), which has collected nearly USD $8 million [21]. Finally, the law does not specify any direct incentives for RE, such as pricing of excess generation, net metering methodology, etc. Therefore, we have evaluated different incentives for RE through a simulation model in order to make recommendations regarding the effectiveness of different mechanisms for forthcoming regulations.

3. Dynamic modeling for renewable energy diffusion

The diffusion of new products is usually modeled as an S-shaped curve, or logistic curve [22]. These curves show the behavior of the adoption of a product in a new market. The S-shaped curve simulates a slow diffusion in the first periods and as the product is adopted by new users, the diffusion rate increases exponentially until market saturation is reached [23]. Bass (1969) proposed the first diffusion model which explains the adoption rate as a function of an innovation coefficient, an imitation coefficient and the total initial potential users. The Bass model evolved to include costs and profitability as decision variables that affect the diffusion rate [25].

Since the early 2000s, diffusion models have been applied to study the penetration of RE in different regions. These models have been used as tools for evaluating regulatory and policy instruments, forecasting future diffusion and describing possible future behavior. The methodologies used in these applications have evolved from econometric estimations in the early 2000s, to system dynamics and agent-based models in recent years. Some studies have also used econometric estimations of several models (logistic, Bass, Gompertz, etc.) to evaluate the diffusion of different RE technologies in Europe [26–28], India [29] and OECD countries [30]. Applications of system dynamics in diffusion of renewable energy include the evaluation of incentives for wind energy worldwide [6] and in Colombia [31], distributed generation of small hydropower in Colombia [32], biomass in Greece [33] and solar PV in Colombia [13,14]. Recently, agent-based modeling has been used for the diffusion of RE in several applications, such as micro-cogeneration technologies [34], plug hybrid vehicles [35], dynamic electricity tariff adoption [36], renewable heating systems [37] and rooftop solar PV adoption [38,39].

In general, we have observed that recent studies about RE diffusion have been focused primarily on the diffusion of wind energy and, to a lesser extent, of solar PV energy. Secondly, studies about RE diffusion have been limited to developed regions, such as Europe and the United States, while analyses in developing countries are still limited. Finally, few studies in Colombia consider the diffusion of RE to be a dynamic system and do not consider the main RE sources in the country. It should be noted that such studies were performed before 2014, meaning they do not evaluate the effects of the new RE law in the diffusion of RE in the country (see e.g. Ref. [15]).

We have selected the system dynamics approach to develop our diffusion model as we are interested in understanding the dynamic structure of the system and explaining the behavior as a result of said structure. This is an appropriate methodology for addressing such interests [40]. The development of the base diffusion model and formulation of incentives for RE in Colombia will be presented in the following sub-sections.

3.1. Modeling the basic diffusion structure

In developing the diffusion model we have considered five RE technologies: SHP, wind, biomass, solar utilities and geothermal. These models could operate independently or, as it is done in an RE market scenario, as a whole. Here we describe the development of a generic model, which is replicated for each technology. The model is based on two main state variables: available potential and installed capacity. Fig. 1 shows the causal loop diagram of the system based on these two variables. The available potential is a

[2] Small hydropower plants have an installed capacity lower than 20 MW. In this study we do not consider large hydropower to be renewable energy given the significant environmental and social impacts.

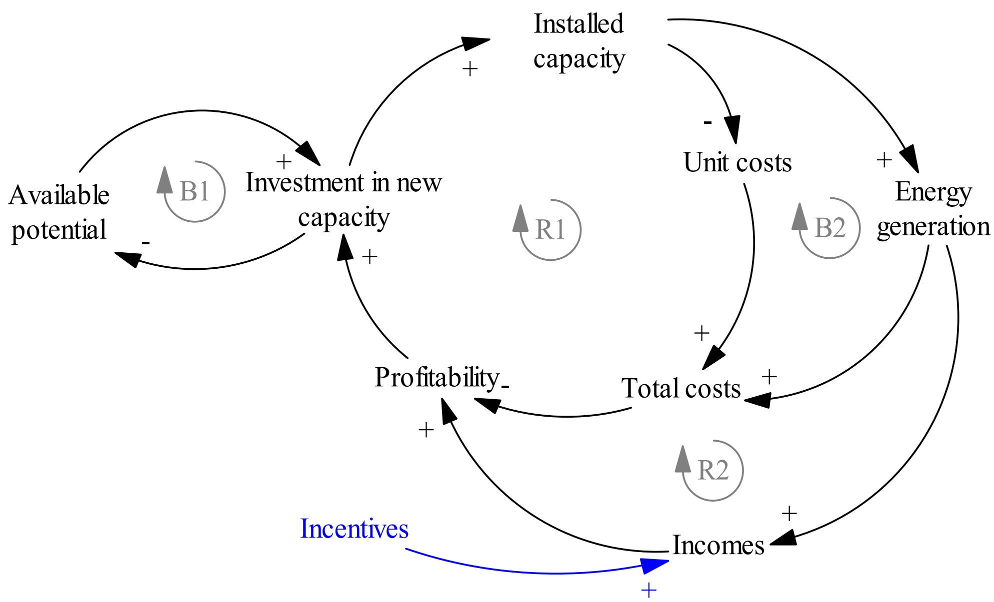

Fig. 1. Causal loop diagram for the base diffusion model.[3]

finite value that represents the total maximum energy that can be installed in the country for a particular technology, taking into account current conditions. This potential decreases when the country invests in new capacity; this new capacity increases the total installed capacity of the technology in the country.

Based on the Bass model [24], we assume that investment in new capacity depends on an exogenous innovation parameter, and an endogenous imitation factor. We modeled the imitation factor as one that depends on the profitability of the technology, which increases with incomes—and therefore with incentives and policies—and decreases with the total costs. Incomes and costs depend on energy generation, price and unit costs. We modeled the learning curve—where the unit costs decrease when the cumulative installed capacity increases—as described by several authors for RE (see e.g. Refs. [41–44]). The causal loop diagram in Fig. 1 shows three reinforcing loops (R1, R2, and R3) that encourage the increase of the installed capacity in an exponential shape, and one balancing loop (B1) that represents the availability of the finite resource and that limits the growing behavior and completes the S-shaped curve. Thus, the cumulative installed capacity reaches its maximum when the total potential is exhausted. Table 1 summarizes the main equations of the model in consistency with this.

3.2. Modeling the incentives

A large number of different incentives exists; a comprehensive historical review is presented by Ref. [48] for RE promotion in the European Union. They classify the regulatory options as investment-focused and generation-based. Several studies agreed that investment-focused mechanisms such as tax exemptions and other indirect mechanisms are less efficient than direct mechanisms (generation-based) in reaching an RE target [31,49,50]. As previously mentioned, the Colombian RE law explicitly declares different tax exemption incentives, but no direct mechanisms for the net metering payment have been established. In this study we evaluate one indirect mechanism of tax reduction (TR) currently included in the Colombian law, and three direct mechanisms based on the experiences of other developed regions: feed-in tariffs (FIT), tradable green certificates (TGC) and technical subsidies (TS) for ancillary services. We also evaluate a combined scenario (CS).

The TR incentive assumes that the aggregate tax rate (T) decreases from 40% to 20% after 2017, and that all energy sources sells their energy at the expected spot price (p_s). Under the FIT scheme, the RE has a market-independent price that increases at a constant rate from 2018 to 2030 [49]. We assumed differentiated tariffs, with different initial prices for each RE technology but the same growth rate [49]. The TGC stablishes a RE quota to be generated, transported and sold to the end user [48]; this quota creates a tradable certificates market, where the price is established through a supply-demand balance. The TS scheme pays an additional amount to the price for the complementary services that SHP and biomass can provide to the grid, such as voltage and reactive power control [51]. Finally, the combined scenario evaluates the impact of implementing a FIT and TS at the same time. The costs of incentives such as TR and TS are assumed by the government, while the costs of FIT and TGC are usually assumed by the end user through the final tariff [48]. We present the description, assumptions, detailed formulation and calculation of the cost of each scenario in Table A2 of the Appendix.

3.3. Model validation

Our model aims to provide insights and lessons for policy development regarding RE in Colombia. As a flexible tool, it can also be validated with soft techniques. According to Barlas [52], validation of SD models should first be focused on the structure of the model, and then on behavior. Following the validation process suggested by Ref. [52], we performed two tests for the model structure: (i) direct structure tests to check the consistency of causal relationships, in which each relationship was formulated based on theories such as the Bass Diffusion Model [24] and learning curves [53], and on direct information from experts in the Colombian energy system. (ii) A dimensional consistency test, performed by checking that the units of all variables guarantee

[3] In a causal loop diagram, the arrow linking any two variables, x and y, indicates that a causal relationship exists between x and y. The sign at the head of each arrow denotes the nature of the relationship as follows [57]: $x \rightarrow^{+} y \Rightarrow \frac{\partial y}{\partial x} > 0$ and $x \rightarrow^{-} y \Rightarrow \frac{\partial y}{\partial x} < 0$.

Table 1
Main equations of the base diffusion model for renewable energy. Subindex i represents the technologies, where $i = \{SHP, biomass, wind, solar, geothermal\}$.

Variable		Equation and comments
Available potential (MW)	P_i	$\frac{dP_i}{dt} = -C_{new,i}$ The available potential is used and decreased with the installation of new capacity.
Cumulative installed capacity (MW)	C_i	$\frac{dC_i}{dt} = C_{new,i}$ The cumulative capacity increases with the installation of new capacity. We assume that for the simulation period (15 years) the installed capacity does not decrease with scrapping since most plants in Colombia have shown to operate for more than 50 years.
New capacity (MW/year)	$C_{new,i}$	$C_{new,i} = \alpha_i P_i + \beta_i r_i P_i \left(\frac{C_i}{P_i + C_i}\right)$ Based on the generalized Bass diffusion model [24,45]. α_i and β_i represent the innovation and imitation parameters, respectively, and r_i the profitability of the technology.
Energy generation (MWh/year)	G_i	$G_i = f_i C_i$ The energy generation is estimated with the installed capacity times the utilization factor (f_i).
Profitability	r_i	$r_i = \frac{I_i}{E_i}$ The profitability is the ratio between the total income I_i and the total expenditure (E_i).
Total incomes (USD/year)	I_i	$I_i = p_i G_i$ We assume that all the generated energy is sold; thus the total incomes are the incomes from energy sold at a price (p_i). Energy prices vary according to the policy mechanisms, and price scenarios.
Total expenditure (USD/year)	E_i	$E_i = c_{capex,i} + c_{opex,i} + c_{tax,i}$ The total expenditure considers capital expenditures, operational expenditures and taxes. We have separated the taxes from OPEX, in order to study an incentive on tax reductions.
Capital expenditures (USD/year)	$c_{capex,i}$	$c_{capex,i} = \frac{j_i(c_{inv,i}C_i)}{1-(1+j_i)^{-\tau_i}}$ The capital expenditure is the total investment costs for the existing capacity, annualized during the investment lifetime (τ_i), with a discount rate j_i. The total investment costs are the unit investment costs ($c_{inv,i}$) times the existing capacity ($c_{inv,i} \cdot C_i$).
Unit investment Costs (USD/MW)	$c_{inv,i}$	$c_{inv,i} = c_{inv,i}(0) * \left(\frac{C_i}{C_i(0)}\right)^{\lambda_i}$ The cost function is a representation of a learning process, where price is reduced with experience, as observed for different RE [46,47]. $c_{inv,i}(0)$ is a reference investment cost in USD/MW related to the initial cumulative capacity $C_i(0)$. λ_i is the elasticity of costs, and the factor $\left(\frac{C_i}{C_I(0)}\right)^{\lambda_i}$ represents the cost correction due to learning [42].
Elasticity of learning	λ_i	$\lambda_i = \frac{\ln(1-LR_i)}{\ln 2}$ We obtained this expression from the definition of learning rate $(LR_i) LR_i = 1 - 2^{\lambda_i}$ [42].
Operational expenditures (USD/year)	$c_{opex,i}$	$c_{opex,i} = c_{o\&m,i}(0) G_i * \left(\frac{C_i}{C_i(0)}\right)^{\lambda_i}$ $c_{o\&m,i}(0)$ are the initial operation and maintenance costs in USD/MWh, related to the initial cumulative capacity $C_i(0)$. We assume that these costs decrease at the same rates as investment costs.
Aggregated taxes (USD/year)	$c_{tax,i}$	$c_{tax,i} = \begin{cases} T(I_i - c_{opex,i} - c_{capex,i}) & if\ (I_i - c_{opex,i} - c_{capex,i}) > 0 \\ 0 & if\ (I_i - c_{opex,i} - c_{capex,i}) < 0 \end{cases}$ T represents the annual aggregated tax rate, paid to the government when the annual profits are positive.
Levelized cost of energy (USD/MWh)	$LCOE_i$	$LCOE_i = \frac{\sum_{t_0}^{t_h} E_i(t)}{\sum_{t_0}^{t_h} G_i(t)}$ The LCOE is the ratio between the sum of expenditures during all the simulated period (from t_0 to t_h), divided by all the energy generated during the same period. t_0 is the initial year and t_h is the time horizon.

mathematical consistency and logical representation according to reality.

For the behavior validation, we cannot perform direct statistical behavior tests, since data on installed capacity of RE in the country are limited.[4] We therefore used the following three structure-oriented behavior tests. (i) We evaluated whether the model behaves according to its structure, with an S-shaped behavior in the long term reaching the maximum value when all potential is installed. (ii) We performed an extreme conditions test, in which the simulation model was tested for extreme values of energy prices, energy potentials, and operational and investment costs; here, we evaluated the behavior of the model if each variable had a value of zero and double its real value. All simulations showed to be coherent with the expected result for each extreme value tested. (iii) We also performed a sensitivity analysis test for uncertainties at the expected energy price, learning rates and available potential, under the baseline scenario.

From the validation process we can conclude that the model is appropriate for its purpose of representing the diffusion behavior of a technology and the learning process about the diffusion of RE in Colombia, as well as for testing different energy incentives including the new RE law.

4. Simulation and discussion of policy scenarios

In this section we present simulation experiments consisting of six scenarios: one baseline scenario (business as usual, or BAU) and its sensitivity to the expected energy price, learning rates and available potential; and five scenarios related to the incentives described in the previous section (TR, FIT, TGC, TS, and CS). Appendix A presents the parameters used for the simulation of all scenarios. We present the evolution over time of installed capacity, profitability and LCOE for BAU scenario, and then compare the results of policy incentives scenarios with BAU.

[4] We checked that, in the absence of incentives, the model replicates the installed capacities for wind, solar and biomass between 2014 and 2017, and we cross-validated the simulation with SHP data from 1900 to 2017.

4.1. Baseline scenario (BAU)

To simulate the BAU scenario we used the parameters from rows 1–10 in Table A1 (See Appendix), assuming the average spot price (p_s) for all technologies, and full tax rate (40%) for all simulated periods. Fig. 2 presents the installed capacity under the BAU scenario. The figure shows that, by 2030, the installed capacity of SHP doubles the 2014 value, reaching almost 1300 MW. The biomass capacity increases from 72 MW in 2014 to 310 MW in 2030, and wind capacity reaches almost 150 MW. The capacity of solar energy increases from 9.8 in 2018 to 116 MW in 2030. Finally, given that geothermal energy does not exist in the country at commercial scale, its deployment is not expected to start before 2030. Colombia reaches a total renewable capacity of around 1900 MW; such amount may not be enough to reach the Colombian RE target. However, the target coverage decreases over the time, given that the RE demand is expected to increase faster than the RE capacity.

Fig. 3 shows the behavior of profitability and LCOE under the BAU scenario. We used historical energy prices for the period 2014–2018. The Colombian electricity market is highly dependent on hydro generation. The increase in energy prices during the drought of El Niño 2015–2016 is observable in a peak in profitability of biomass, geothermal, wind and solar, and a decrease in SHP. During 2017–2018, after El Niño was over, energy prices stabilized again, and profitability reached the average values. After 2018, all technologies showed increasing profitability although at different rates. The two mature technologies existent in the country (SHP and biomass) showed to be profitable during the period 2018–2030, given that they have smaller LCOE than the spot price. Wind energy showed a profitability lower to one after El Niño but it recovers after 2022 and reaches the highest profitability in 2030. This increase is a result of the learning-by-doing process, given that the wind installed capacity reaches almost eight times the initial value (i.e., the capacity doubles almost three times). The profitability of solar energy is lower than one before 2022. Despite this, the urge to diversify the energy mix lead to the installation of the first plant in 2017. Thus, LCOE is then expected to decrease as a result of learning by doing, which translates into an increasing profitability. By 2030, solar energy is almost as profitable as SHP. Finally, since geothermal energy is not developed in the country before 2030, the high LCOE remains constant, and thus the profitability is lower than one during all the simulated period.

We performed a sensitivity analysis of the results to variations in the expected energy price of ±50% from the average, such that extreme prices that have been registered during drought periods are covered. We observed that such variations do not affect the final results pertaining to total installed capacity and RE target coverage. This is due to the fact that geothermal and solar technologies would maintain low profitability even at the maximum price, while SHP, biomass and wind technologies can still be profitable at the minimum prices.

For learning rates, we tested sensitivity to ±20% of the values reported in Table A1 of the Appendix. The total installed capacity and coverage of the RE target are also insensitive to these variations since SHP and biomass contribute 87% of the total capacity, and the results for these technologies are mostly unaffected (changes <1% of their profitability and capacity). Learning has a greater impact on the technologies with less maturity in the country, such as wind,

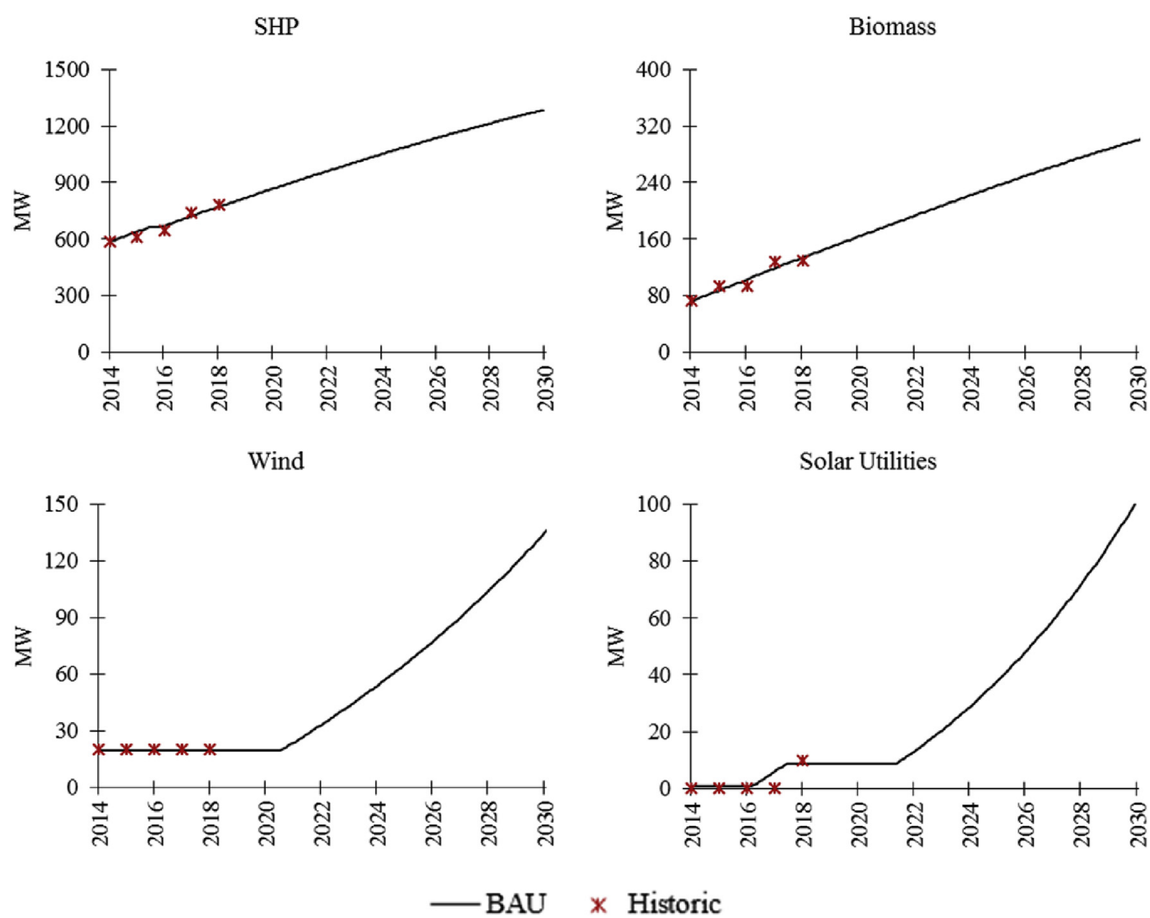

Fig. 2. Installed capacity under BAU scenario.

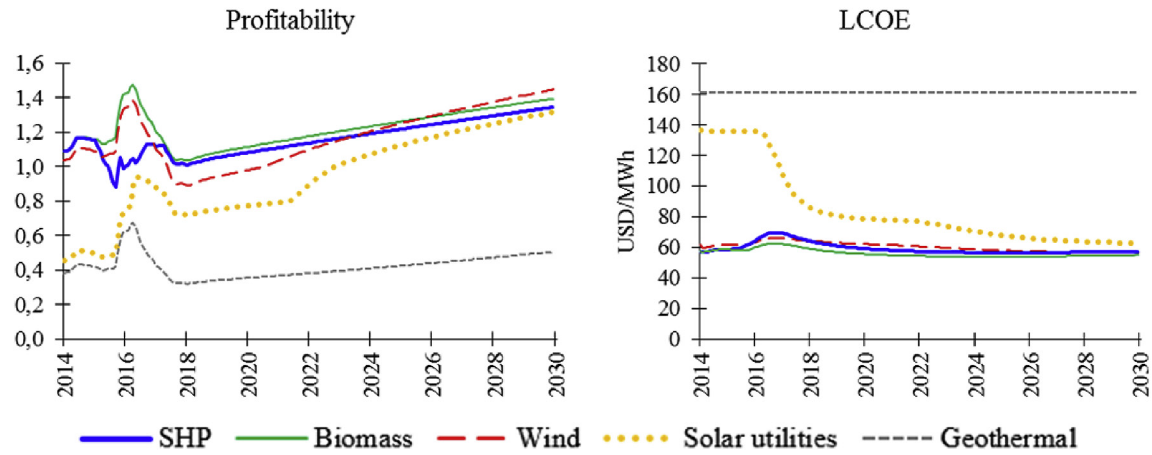

Fig. 3. Profitability and LCOE under the BAU scenario.

solar and geothermal. For these technologies, LCOE and profitability can vary up to ±10%. This can modify wind and solar capacity by ±5% but does not affect the geothermal capacity, since even in the best of cases it will remain unprofitable.

Finally, we tested for the uncertainties in available potential with the minimum values reported in Table A1 of the Appendix, and increasing up to 20% with a normal distribution. The results showed to be more sensitive than for price and learning rate (see Fig. 4), with the coverage of the RE target varying between 40 and 48%, and the total installed capacity between 1700 and 2200 MW.

4.2. Policy incentive scenarios

Table 2 presents a summary of the results for the five incentives by 2030, and the percentage change compared to the BAU scenario.

As shown in Table 2, the TR scenario can favor the installation of SHP, biomass, solar and wind in the country, but does not impact the diffusion of geothermal energy. As explained by Table A2 (see Appendix), a particular technology is taxed when the activity generates a positive net income; conversely, the technology is not profitable, and therefore is not taxed. A reduction in the tax rate therefore benefits only those technologies that are currently profitable, i.e., with profitability greater than 1. Similarly, the simulations of TR showed no changes for the diffusion of geothermal during the 16 simulated years.

For SHP, biomass, solar and wind, the TR scenario showed an impact mainly on profitability and LCOE, given that the amount of money paid in taxes decreases. The increase in profitability has a positive though small effect on the installed capacity. The improvement in the total RE capacity of the country is small, adding up to only 37 MW of new capacity, with a cost of 4.75 billion dollars for the government.

The differentiated prices proposed in the FIT scenario mainly favor wind, solar and geothermal deployments (see Table 2). These three technologies showed improvements in both installed capacity and profitability, which leads to an increase in the paid taxes. The simulations showed that the FIT incentive has a small effect on the average energy price for the end user, which could increase by 1.3% in the first years after the entrance of the incentive. This increase in price is small because the designed tariff pays more only to the less adopted technologies (wind, solar, and geothermal), while SHP and biomass have FIT tariffs similar to the expected price.

The results of the TGC scenario show that the installed capacity of all technologies increases by 2030, given the high prices of the green certificate (see Table 2). Another effect is that the profitability of solar and geothermal reaches values greater than one after 2020. However, the green certificate price is reflected in a high increase in the average price of energy for the end user, because all RE sell their energy at the maximum price. The increase in the incomes of the technology causes an increase in the collected taxes of more than twice of the BAU. With the increase in taxes, the LCOE for all technologies shows an increase over time, except in the case of geothermal energy, which reaches equilibrium between the reduction by learning and the increase in taxes.

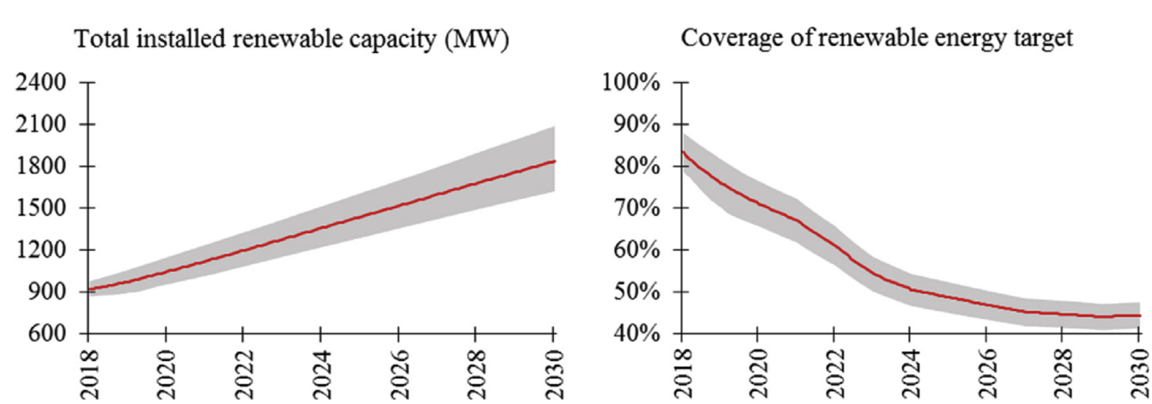

Fig. 4. Sensitivity of total capacity and RE target to the available potential. Red line: Average value. Grey area: Range of maximum and minimum values. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Simulation results of all scenarios by 2030. Percentages in parenthesis indicate the change compared to the baseline scenario.

	TR	FIT	TGC	TS	Combined Scenario
SHP					
Installed Capacity (MW)	1338 (1%)	1324 (1%)	1352 (2%)	1352 (2%)	1357 (3%)
Profitability	1.57 (14%)	1.38 (0%)	1.36 (-1%)	1.51 (10%)	1.52 (11%)
LCOE (USD/MWh)	53.8 (-7%)	58.8 (1%)	65.0 (12%)	65 (13%)	66.12 (15%)
Biomass					
Installed Capacity (MW)	319 (3%)	312 (1%)	320 (3%)	320 (3%)	322 (4%)
Profitability	1.66 (17%)	1.43 (0%)	1.41 (-1%)	1.56 (10%)	1.56 (10%)
LCOE (USD/MWh)	50.4 (-9%)	56.6 (2%)	61.7 (11%)	63 (13%)	64 (15%)
Wind					
Installed Capacity (MW)	159 (5%)	203 (35%)	203 (35%)	150 (0%)	203 (35%)
Profitability	1.78 (20%)	1.61 (9%)	1.51 (2%)	1.48 (0%)	1.61 (9%)
LCOE (USD/MWh)	50.7 (-10%)	60 (6%)	58.2 (3%)	56.5 (0%)	60 (-6%)
Solar utilities					
Installed Capacity (MW)	123 (5%)	207 (77%)	193 (66%)	117 (0%)	207 (77%)
Profitability	1.54 (14%)	1.61 (19%)	1.4 (4%)	1.35 (0%)	1.61 (19%)
LCOE (USD/MWh)	58.2 (-7%)	70 (11%)	60.8 (-3%)	62.9 (0%)	70 (11%)
Geothermal					
Installed Capacity (MW)	1 (0%)	25 (+100%)	89 (+100%)	1 (0%)	25 (+100%)
Profitability	0.53 (0%)	1.36 (158%)	1.21 (130%)	0.53 (0%)	1.36 (158%)
LCOE (USD/MWh)	161 (0%)	111 (-31%)	64.53 (-60%)	161.3 (0%)	111 (-31%)
Total renewable capacity (MW)	1939 (2%)	2071 (9%)	2156 (14%)	1940 (2%)	2112 (11%)
Coverage in RE target (%)	44%	45%	46%	45%	46%
Maximum increase in average expected price for end user	0%	1.3% in 2019	14% in 2018	0%	1.3% in 2019
Cumulative tax collection in the period 2018–2030 (Mill USD)	4930 (-50%)	12428 (28%)	20000 (+100%)	19156 (98%)	22000 (+100%)
Total governmental cost of the incentive in the period 2018–2030 (Mill USD)	4750			13428	10731

The results for the TS scenario show that the technical incentives could increase the installed RE capacity and profitability, in addition to the technical benefits for the electric system. The coverage in the RE target is similar TGC scenario but avoiding the undesired effects on the average price for the end user (see Table 2). However, in this case, the government has to bear the high cost of the subsidy, of more than 13 billion dollars (about 750 million per year). Since the technical incentive can also increase the incomes for distribution utilities, given that it improves the electricity supply continuity, the government could design a mechanism that distributes the cost of the subsidy between all the benefited parties.

The combined scenario considers a differentiated price (FIT), and the subsidies presented in the TS scenario. This scenario showed a similar output to TGC, with a small increase in the expected price for the end user, and a high cost for the government (more than 10 billion dollars). As shown in Table 2, none of the scenarios guarantees coverage of 100% of the RE target, which suggests that the energy demand will grow faster than RE capacity. Thus, demand-side incentives will be necessary to reach the Colombian RE goals.

As mentioned, Colombia faces the challenge of diversifying its hydro-dependent energy mix, its share has remained the same since 2000. Since RE in the country cannot compete with coal and hydro in terms of costs or resource and energy security, appropriate policy design is necessary to guarantee the entry of renewables into the Colombian portfolio. Consistent with previous studies, we found that incentives are necessary to promote RE in Colombia. Moreover, our results show that, to reach the RE target, Colombia will need direct generation-side incentives such as TGC or FIT tariffs, similar to the conclusion in other studies around the world (see e.g. Refs. [12,49,50]), and demand-side incentives [14,15]. The energy market has been dominated by capacity mechanisms (capacity and reliability charges) for the last 15 years [54], and although the new RE law seeks to promote RE and diversify the mix, such capacity mechanisms may continue to slow the diffusion of RE in the country.

Finally, another challenge for Colombia is to reduce electricity demand and improve energy efficiency. The country currently has some intermittent demand management programs, particularly during drought periods, with incentives mainly directed towards the industrial sector. In addition to diversification policy, the country needs to design massive and periodic programs that benefit not only the industrial sector, but also other economic sectors as well as all agents of the energy market.

5. Conclusions

Colombia currently faces the challenge of diversifying its energy system by introducing new renewable energy technologies, not only as a means of reducing GHG emissions, but also to adapt to climate change. Given the high dependency on hydropower (70% of the energy mix), the power sector is highly vulnerable in dry periods, especially during El Niño phenomena, which are becoming longer and more intense with climate change. Incentives to promote RE are therefore necessary for the country.

In this study, we developed a system dynamics model to assess the effect of different incentives on the diffusion of RE in Colombia. The Colombian government introduced the RE law in 2014 (Law 1715/2014) which considers only indirect incentives related to tax reductions (TR). We found that the implementation of this law is not enough to stimulate the diversification of the energy mix. Consistent with the experiences of other countries [52], we found that direct incentives such as feed-in tariffs (FIT) and tradable green certificates (TGC) have stronger effects on the diffusion of RE.

According to our simulation model, the TR incentive favors the development of those technologies currently implemented in the country, such as SHP, biomass, solar and wind. A 50% reduction in income tax would increase RE profitability by over 14%. However, this incentive does not improve the development of new technologies such as geothermal. Based on the simulations we can therefore conclude that this is not an effective incentive, due to the fact that it increases the total RE capacity only 2% by 2030 compared with the BAU scenario, and that it fails to diversify the energy mix.

The FIT scenario showed a modest increase in the total installed capacity by 2030 (5% compared to BAU). However, it supports energy mix diversification, as the differentiated tariff favors the development of wind, solar and geothermal energy. Still, the share of these three technologies in the aggregated system would remain small compared to other sources. FIT showed to be more effective than TR, and at a lower cost for the government.

The TGC scheme and combined scenario showed the best results, with an increase of 14% and 11% of RE by 2030, respectively. Moreover, they both favor diversification, since it promotes the development of all the RE considered in this study. The main difference is that, under the TGC scheme, the cost of the incentive would be transferred to the final user. The high price of the certificate would increase the average energy price up to 14%.

We established an RE target of 20% of capacity for 2030. We found that none of the scenarios or policies can reach such a target, given that the electricity demand will increase at a greater rate than the RE deployment. This suggests that the currently available potential will not be sufficient to cover the increasing demand. In the model we assumed an RE potential equivalent to the capacity of the RE projects registered with the Ministry of Energy. This result suggests that the current projects will not be enough to cover the RE target, and therefore more RE projects should now be supported and developed, in order to increase mid-term potential and to be able to succeed in meeting the target.

In order to overcome the sharp hydro-dependency, Colombia needs to include new energy sources on the market, and implement permanent programs of energy efficiency and demand management. However, the main barrier to the adoption of RE in Colombia is the current existing policy on the capacity mechanisms, implemented in the early 2000s and still in force, which has favored traditional energy. The country therefore needs incentives that are more effective than those currently formulated in the RE law; otherwise, the composition of the energy mix is expected to remain as it has been for the past 15 years.

Future work should modify the previous model to include updates to RE Law that are being issued recently such as resolutions 40791 and 40795 of 2018, which establishes large renewable capacity auctions. A long-term energy auction will allow a greater incorporation of renewable energies into the national energy system; the auction will be held in January 2019 for an amount of 3443 GW per year, equivalent to approximately 1000 MW of installed capacity [55]. New resolutions also define the parameters for self-generation scales, excluded from this study. From the demand side, we recommend future work to focus on the effect of self-generation on the decrease in energy demand, and the final user's willingness to pay for RE.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.renene.2019.02.138.

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