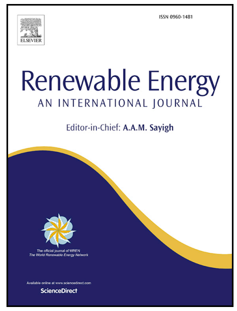
Accepted Manuscript



The prospects for Small Hydropower in Colombia

Jessica Arias-Gaviria, Bob van der Zwaan, Tom Kober, Santiago Arango Aramburo

PII: S0960-1481(17)30064-2

DOI: 10.1016/j.renene.2017.01.054

Reference: RENE 8493

To appear in: *Renewable Energy*

Received Date: 12 January 2016

Revised Date: 21 January 2017

Accepted Date: 23 January 2017

The Prospects for Small Hydropower in Colombia

Jessica Arias-Gaviria[1,*], Bob van der Zwaan[2, 3, 4], Tom Kober[5, 2], Santiago Arango Aramburo[1]

[1]Universidad Nacional de Colombia, Decision Sciences Group, Facultad de Minas, Medellin, Colombia
[2] Energy research Centre of the Netherlands, Policy Studies, Amsterdam, The Netherlands
[3] Johns Hopkins University, School of Advanced International Studies, Bologna, Italy
[4] University of Amsterdam, Faculty of Science, Amsterdam, The Netherlands
[5] Paul Scherrer Institut, Laboratory for Energy Systems Analysis, Energy Economics Group, Villigen, Switzerland

[*] Corresponding author: Tel: +57 3164441317, jariasg@unal.edu.co

Third Resubmitted Version
NOT FOR QUOTATION OR DISTRIBUTION
January 2017

Abstract
Small hydropower (SHP) has existed for more than a century in Colombia, and is gaining reserved interest as an option to mitigating climate change. In this paper we investigate the prospects for SHP in Colombia based on an analysis of economies-of-scale and learning-by-doing effects. We created an inventory of SHP plants realized in Colombia between 1900 and 2013, and focused on grid-connected SHP stations only. In the economies-of-scale part of our analysis we considered all SHP plants with a capacity lower than 20 MW. However, we exclude plants with a capacity lower than 0.1 MW from the learning-by-doing analysis, given that their cumulative capacity is still too small for a meaningful learning curve estimation. We used an Ordinary Least Squares analysis for estimating the parameters of our economies-of-scale and learning-by-doing models, and observed that infrastructure costs and total costs are mainly driven by economies-of-scale, while equipment costs can also be influenced by learning-by-doing. Our findings suggest that equipment costs for SHP plants with capacities between 0.1 and 20 MW have declined at an average learning rate of 21%.-We conclude that both the public and private sectors can benefit from scaling effects for hydropower plants.

Keywords: hydropower, climate policy, investment costs, learning-by-doing, economies-of-scale, Colombia

Nomenclature

α	Parameter of cost reduction by learning-by-doing
λ	Parameter of cost reduction by economies-of-scale
C	Specific cost
C_x	Specific cost for a plant of capacity x
C_{x^*}	Specific cost corrected for economies-of-scale to a reference capacity x^*
C_0	Specific cost at initial time
C_t	Specific cost at time t
LR	Learning rate of the technology
PR	Progress rate of the technology
x	Plant capacity
x^*	Reference plant capacity
X	Total installed capacity of SHP in Colombia
X_{cum}	Cumulative installed capacity in Colombia
$X_{cum,0}$	Cumulative installed capacity at initial time
$X_{cum,t}$	Cumulative installed capacity at time t

1. Introduction

As reported by the recently published Working Group II contribution to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the impacts of global climate change are becoming increasingly evident [1]. Meanwhile, the Working Group III contribution to IPCC AR5 shows that anthropogenic emissions of greenhouse gases (GHG) grew by 81% between 1970 and 2010, while 34% of these additional emissions came from the energy sector, mainly through the combustion of fossil fuels [2]. If mankind wants to limit the global average temperature increase to well below 2°C, low-carbon energy options should come to provide the majority of energy supply over the next several decades [2]. Among the main GHG mitigation options for the energy sector are renewable energy technologies (RET). The Sustainable Energy for All Program (SE4All) of the United Nations has set three critical objectives for 2030: ensuring universal access to modern energy services, doubling the global rate of improvement in energy efficiency, and doubling the share of RET in the global energy mix. These objectives are essential to reach the Millennium Development Goals [3]. Small hydropower (SHP) is a RET that in many regions could substantially contribute to yielding access to electricity. SHP is especially attractive for developing nations, as in several of these countries there are large hydropower potentials, and SHP generates smaller social and environmental effects than large hydropower plants. Colombia is a good example in case, since it has the second largest hydropower potential in Latin America, after Brazil [4]. In this article we investigate the prospects for SHP in Colombia, based on a cost analysis of past deployment activities for this technology.

With a share of 16% of global electricity production and an estimated global technical potential of 3.72 TW, which is four times the currently installed capacity, hydropower is currently the main source of RET [5]. The International Energy Agency (IEA) concludes that hydropower will remain economically competitive, given its low operational costs advantage and long lifespan [5]. However, large hydropower projects have considerable constraints, as they sometimes involve relocation of nearby communities. The construction of large dams also often carries a significant environmental footprint, because reservoirs modify a river's ecosystem. Additionally, there is evidence of GHG emissions from hydropower plants, especially in tropical areas, as a result of decomposition of organic material deposited in the dam reservoirs [6–8]. Thus, SHP plants are an attractive alternative for developing countries, because they can be exploited with usually much smaller social and environmental effects than large hydropower plants [4].

In 2015, Colombia had a total installed electricity generation capacity of 16.4 GW, with a share of 62.1% of large hydropower (plants with an installed capacity bigger than 100 MW), 4.2% of medium hydropower (20 – 100 MW), and 3.7% of SHP (< 20 MW) [9]. The remaining 30% corresponded mainly to thermal generation, as shown in Fig. 1. The hydropower dominance is the result of both low costs and high hydro potential in the country. In Colombia, a technical potential of about 93 GW for all hydropower combined is estimated [4]. There are no studies dedicated to the feasible potentials for SHP only in Colombia. However, the bank energy projects of the Mining and Energy Planning Unit (UPME[1]) shows that the country can reach an SHP installed capacity of 1.8 GW by 2020 and 2.1 GW by 2030, if all current projects materialize [10]. Efforts to build new plants and properly exploit the large hydropower potential are increasing, not only from the government, but also from the private sector. Thus, it is expected that installed capacity gradually increases in the long term, as economic and technical gaps are filled.

Fig. 1

Since hydropower is a mature technology, future cost reductions are expected to be less significant than those still realizable for other RET, such as solar and wind power [5]. Even so, continuing to stimulate the diffusion of SHP in Colombia is attractive, because, on the one hand, SHP presents an opportunity to make power production technically feasible at reasonable costs in many different locations, and, on the other hand, the performance of both new and existing projects can still be improved. In order to support the stimulus process, both the public and private sectors can benefit from an analysis of the drivers of cost reductions for SHP deployment in Colombia, including effects like economies-of-scale (EOS), learning-by-doing (LBD), research and development (R&D) and directed policy instruments. Such analysis is particularly pertinent in the context of the growing interest today for new SHP investments in Colombia, given its large hydropower potential and the attractiveness of this technology for supplying electricity to non-connected areas.

In this paper we present a study based on an inspection of both EOS and LBD for SHP in Colombia, particularly for plants with capacities between 0.1 and 20 MW. Section 2 of this article presents the historical evolution of SHP in Colombia. An assessment of SHP costs in Colombia is presented in section 3. Sections 4 and 5 present our EOS and LBD analysis. Discussion and conclusions, as well as a presentation of the limitations of our analysis, are provided in section 6.

[1] The Mining and Energy Planning Unit (UPME) is the Colombian entity responsible for planning the exploitation and develepment of the energy and mining resources.

2. Evolution of Small Hydropower in Colombia

The exploitation of Colombian hydro potential dates back to 1900, when a power plant of 1.86 MW was built to supply electricity to Bogotá, the largest city and Capital of Colombia [11]. Since then, more than 200 SHP plants have been built to electrify different regions in the country. A timeline for SHP in Colombia is presented in Fig. 2. By 1930, the installed capacity of SHP in Colombia had reached almost 35 MW and it continued increasing until the late 1960s. During the 1970's only few plants were built and some old ones were decommissioned, mainly due to lack of maintenance and the start of the roll-out of grid-connected large hydro [12]. Delays in construction of large plants while demand was rapidly growing, however, led to an energy crisis in the late 70s, and a blackout in 1983 [12]. Hence, the government started to promote the use of non-conventional energy and the recovery of old hydro plants in 1985. By the end of the 1980s, the cumulative installed capacity of the country was about 320 MW of SHP, but only about 50% was in operation.

In the early 1990s, hydropower plants represented 80% of the total installed capacity which made the Colombian electricity sector highly vulnerable to sufficient water availability. Low levels of rain caused by El Niño[2], which causes in Colombia more extreme and longer dry seasons than usual, reduced the country's total water reservoirs below 40% in 1992, and led to another energy crisis. This situation, and mismanagement in the power sector, resulted in major blackouts between 1992 and 1993 (for further information see [13]). The lack of the government financing of the required expansion of the electricity system, and the ambition to increase the efficiency of the power sector were important driving forces for the deregulation of the power system and the establishment of a liberalized electricity market in 1994 [14]. The new electricity market was introduced with the Electric Law in 1994 [15], by which the private sector started to participate in the electricity market, and different funds for rural electrification were created. As a consequence, programs for installation of SHP in both grid and non-grid connected areas[3] have been developed, which led to an increasing interest in SHP with 363 MW being newly installed during the last three decades, reaching a total cumulative installed capacity of SHP of 683 MW in 2014, from which 620 MW are in operation, and 530 MW are connected to the national grid.

Fig. 2

The definition of SHP varies widely across different sources in the literature: the upper limit for the plant capacity[4] ranges between 1.5 and 100 MW [16]. In Colombia, the UPME has adopted the IEA definition of SHP, that involves a plant capacity less than or equal to 20 MW [17] and that operates at run-off-river, with no water storage. From the market integration perspective, current Colombian rules do not require plants under 20 MW to participate in the trading process of the Colombian electricity market. Operators of these SHP can choose to sell energy at the market's pool price or at a bilaterally agreed price with a buyer. In order to consider a more detailed differentiation of SHP in this study we classify SHP into three further categories according to the size of the plant, as shown in Table 1.

Table 1

[2] El Niño and La Niña are opposite phases of what is known as the El Niño-Southern Oscillation (ENSO). El Niño is characterized by unusually warm ocean temperatures in the Equatorial Pacific, as opposed to La Niña, which is characterized by unusually cold ocean temperatures in the Equatorial Pacific [37]

[3] The non-grid-connected areas in Colombia are defined as all the municipalities, town and villages that are not connected to the national grid, excluding those with viable conditions for interconnection [38].

[4] Note that we use capital *X* for the cumulative capacity of the country, while the small *x* refers to individual plant capacity.

For the purpose of this study we have established a database containing historic data of SHP plants in Colombia. Different sources were consulted such as documentations of governmental SHP programs, records of private electricity generation companies, academic master thesis and PhD thesis, technical infrastructure expansion planning reports from power utilities and governmental bodies, as well as interviews with experts for SHP in Colombia. The SHP database contains information of each individual plant, including construction year, installed capacity, location and current state of operation[5]. Furthermore, information about investment costs for different SHP projects between 1900 and 2013 is included. Based on the data collected, we calculated the annual new capacity of the country by summing the capacity of each new plant. With the annual new capacity data, we calculated the cumulative capacity by adding the yearly new capacity to the value of the previous year, as shown in Fig. 3. We explicitly include plants which are not more in operation (which represent 9% of the current cumulative capacity), because the experience in the construction of those plants contributed to the learning process that this study wants to evaluate. This also means that scrapping and lifetime were not considered for the calculation of cumulative capacity for this analysis.

Fig. 3a presents the consolidated total annual new capacity and cumulative capacity evolution, including all three categories listed in Table 1. Two periods of low investment activity are observed (1960-1969 and 1975-1985), which correspond to the previously mentioned energy crises. Low activity can also be observed around World War I and II. As we can see from Fig. 3a SHP cumulative capacity has been doubled in Colombia over the past 3 decades.

For each capacity category (small, mini and micro), the cumulative capacity developments are presented in Fig. 3b, 3c and 3d respectively. The figures show that 95% of the total cumulative capacity belongs to small plants, 4.9% to mini, and only 0.1% to micro. Almost all micro plants have been built after 1980. Construction of new mini centrals has remained approximately constant with only 28.4% of the cumulative capacity built after 1980, while for micro and small plants 90% and 54% of the cumulative capacity has been built in the last 3 decades, respectively.

Fig. 3

3. Cost assessment

Specific investment costs[6] reported for historic installations of SHP in developing countries fall typically in a range of 1000 and 8000 USD[7] dollars per kW, with few values outside of this bandwidth [16]. Almost all cost data we gathered for this study falls in this interval with very few outliers for SHP in non-connected areas, which expands the range from 900 USD/kW to 9400 USD/kW[8]. Fig. 4, which shows the distribution of specific total costs[9] over time, shows that costs in non-connected areas yield larger variations in comparison to those in grid-connected areas. Due to lack of information on the cost components of investments costs for non-connected installations (which might we driven by

[5] For further detail, see the SHP database with the inventory and cost data in the suplementary material, available in the web version of this document.
[6] Hereinafter, the term "*cost*" is used to refer to *specific cost*
[7] If not stated otherwise, monetary units reported in this article refer to US Dollar (USD) based on the year 2013.
[8] Due to limitations in the availability of costs data, it was not possible to consider cost data for all SHP plants included in the SHP database.
[9] As some of the cost data were presented in Colombian pesos, they were converted to United States dollars with the average exchange rate of the corresponding year, reported by the Bank of the Republic of Colombia [39], and then converted to (2013) USD using the annual inflation rate reported by the US Bureau of Labor Statistics [40].

ancillary equipment and not by the costs for the turbine part) we exclude these plants from our analysis[10].

Fig. 4

Total investment costs comprise different cost components, which can be distinguished into *equipment costs*, *infrastructure costs*, *and other costs* as shown in Fig. 5 [17] . Where data availability allowed, we took these cost components in our dataset of SHP plants into consideration. Not all literature sources provided information on all four types of costs, which explains why our four costs components display a different number of plants, even when they cover the same time horizon. Even so, this does not constitute a limitation for our analysis, given that each set is treated independently.

The historical costs for SHP in grid-connected areas, clustered by capacity categories, are presented in Fig. 6. Even though, the data points are rather scattered, a tendency with respect to the magnitude of installed capacity can be observed. This suggests an EOS effect, which needs to be taken into consideration when calculating the LBD effect. Otherwise, cost reductions over time could partly result from EOS instead of LBD. We separate the EOS effect from the cost data following the procedure as suggested in [18]. For the calculation of EOS and LBD effects we also exclude the component *other costs*, because they are not comparable as a result of the fact that the consulted sources differ on the items included in this category (e.g. not all the sources report the environmental costs). Also, we assume that the items in the category *other costs* are not affected by LBD and EOS.

Fig. 5
Fig. 6

4. Economies-of-scale

EOS effects describe the relation between the level of production and the associated production costs or return rate [19]. EOS effects can be investigated at different layers of depth where EOS models can include multiple input variables, such as scale of production, hours of labor, fuel price, capital [20]. We conduct our analysis on an aggregated level with one input parameter for EOS. Consequently, in our context, EOS exists when an increase in the amount of installed power plants results in a reduction of specific investment costs. Typically, EOS effects for energy technologies are modeled as shown in Equation (1) [21]. In this equation the specific cost C ($/kW) depends on the installed capacity of the plant x and the parameter λ, where λ is the rate at which the unit costs decrease when the capacity increases. The parameter a is an equivalent cost for a plant of 1 kW.

$$C = a\,x^{\lambda-1} \qquad (1)$$

In order to make cost data comparable, we normalized the EOS effects to the same reference capacity as shown in equation (2). In this equation, C_{x^*} refers to the normalized cost for a reference capacity x^*, C_x represents the reported cost for the capacity x, and λ is the same parameter from equation (1) (see e.g. [18]). Normalizing EOS effects provides an improved comparability across different plants, which allows to analyze LBD effects.

[10] Hereinafter we use the SHP acronym to refer to grid-connected plants.

$$C_{x^*} = C_x\left(\frac{x}{x^*}\right)^{1-\lambda} \quad (2)$$

Several studies have demonstrated EOS effects of SHP (see e.g. [22–24]). To our knowledge, detailed studies about EOS for SHP in Colombia do not exist, however some authors have observed cost reductions [17]. When plotting cost data against the installed capacity, as shown in Fig. 7, our data depicts typical behavior of EOS, i.e. there is a decreasing cost trend at increasing installed capacity.

Fig. 7

We used an Ordinary Least Squares (OLS) method for all our data points to estimate the scale parameter $(1-\lambda)$ for each cost category(total, equipment, and infrastructure) and for each SHP size cluster (micro, mini and small plants). In order to avoid dynamical effects such as LBD in the costs data, the time span from 1985 to 2013 is divided into smaller intervals.[11] Table 2 presents the scale parameters $(1 - \lambda)$ estimated for equipment, infrastructure, and total costs for defined time intervals. For the purpose to test the significance of the estimated parameters we employ a standard *t*-test from the standard error of the regressions. Therefore, we calculated the scale parameter for Colombia as the average of the significant estimates in Table 2.

Table 2

Table 3 presents the estimations for the scaling parameter reported by other recent studies, as well as the average of all the estimations for Colombia and abroad. For equipment costs, the total average value is 0.218, the minimum reported value is 16% lower than the average and the maximum value is 32% bigger than the average. The average parameter for infrastructure costs is 0.352, with a relative variation of -32% and +12%. The average value for total costs is 0.326 with a percentage variation of -33% and +23%. Some studies have observed variations to the scale parameter for different types of turbines [25], which may explain the wide ranges of variation. The scaling parameter may not be comparable among different countries, and a detailed analysis of the SHP markets around the world would provide further insights on the comparability of this parameter across countries. Since such an analysis would go beyond our scope, we used the total average to approximate the correction for the EOS effects. In addition to the calculation of the EOS based on the averages of the scaling parameters we tested the sensitivity of the parameters, varying each parameter between its maximum and minimum value (see Table 4).

Table 3

Fig. 8 shows the total costs of SHP after the scale correction over time. There is no evidence that the total costs are affected by LBD, mainly because the scale-corrected data does not present a decreasing trend over time (Pearson's coefficient "r" is positive and close to zero), as it is shown in the figure. The total costs can be influenced on the one hand by EOS and LBD effects (e.g. related to costs for infrastructure and equipment), and on the other hand by exogenous elements, which influence other cost components. We conclude, that LBD can hardly be analyzed in such aggregated information. As a result, we exclude total costs of the LBD analysis, and perform the analysis for the other two cost categories only: infrastructure and equipment.

[11] In the period-clustering we excluded the time before 1985 because this period lacks sufficient data points for dividing them into smaller periods.

Fig. 8

Fig. 9 displays the scale correction for infrastructure costs, which show a more uniform distribution of data points than observed for the total costs. With a slightly negative Pearson's coefficient "r", infrastructure-related costs depict a week decreasing trend over time. After the *t*-test analysis, however, we could not observe a significant behavior that could explain a LBD effect. Instead, data points tend to remain on the same interval (300 – 1800 USD/kw), with some outliers. The variation over time observed in Fig. 6 can be explained by EOS. Moreover, we excluded the infrastructure cost from the LBD analysis, because LBD appears to have little impact on these costs. One possible explanation is that the increasing environmental and social constraints in the construction activities could have balanced or limited the benefits from LBD process. It is possible to analyze the materials cost reduction as a result of a learning process, but it goes beyond the objective of this study, and could be a potential topic for further research.

Fig. 9

The scale-corrected data for equipment costs are less scattered than the non-corrected, as shown in Fig. 10. The figure shows a decreasing tendency of costs over time, which is a typical behavior of LBD. One can observe some outliers in the dataset[12] depicted as not filled points in Fig. 10. Although the correlation of the data points is rather small ($R^2 << 1$), the behavior of the corrected data shows a significant declining trend (Pearson's coefficient "r" is negative and higher that for infrastructure costs, and the *t*-value is greater than *t*-critical). This suggests that further analysis is needed. A reduction of equipment costs is expected as a result of technological change and innovation processes in the manufacturing and installation of electromechanical equipment. Such effects can be investigated by a LBD analysis which provided in the next section.

Fig. 10

The analysis presented in this section showed that SHP plants are affected by EOS. This suggests that both the public and private sectors should focus on small and mini plants, rather than micro plants if a least-cost deployment of SHP is envisaged. Installation of micro plants started after 1980, as shown in Fig. 3d, most of them for electrification of non-connected areas. Other micro plants were built as individual installations to provide electricity for e.g. small farms, industries, and hotels. In order profit from EOS for the SHP, owners should pool with their neighbors and between communities to invest in larger plants. Government should evaluate the viability to electrify several non-connected areas with the same SHP plant, rather than building one micro plant for each community. This, however, strongly depends on the costs to set up the mini-grid infrastructure.

The existing hydropower plants, regardless of the scale, can also benefit from EOS for the operation cost. Filippini & Luchsinger [22] present an EOS analysis in the Swiss hydropower sector considering data like production capacity, operational costs, and number of operated plants, for sizes from small (run-off river) to large (pump-storage). They showed that operating several hydropower plants is more cost-efficient than operating only one plant. Thus, the owners of current and future plants have the potential to reduce their operational costs by joining forces and operating all plants as a single agent.

[12] Point in 1910: The source does not specify if the reported value correspond to investment or equipment repair. Points in 1999 and 2011: Correspond to particular applications for improvement of an integrated public services system. These three points were excluded from λ and *LR* estimations.

5. Learning-by-doing

Learning curves are empirical models commonly used to study the technological change as a result of learning. In this paper we consider learning as the knowledge gained through repeating a process, i.e., increasing production capacity brings learning because it involves repetition and thus specialization of activities [28]. Learning may involve different processes, such as innovation in materials [29], R&D [30], global and local phenomena [31], etc., but given the quality of data, we cannot differentiate among the effect of other processes. Learning curves have been applied in manufacturing, business management, and organization studies, among others. Recently, it has also been used for policy analysis of RET [32]. In this section we estimate the learning curves for equipment costs of SHP in Colombia. We explore the existence of LBD for each capacity category previously described: mini, micro and small plants.

In the previous section we observed a typical behavior of LBD in the scale-corrected equipment costs. As the adjusted tendency was not significant, we have broken down these corrected data by capacity category, as shown in Fig. 11. Here, a cost reduction over time is also observed for each category. Given that the decreasing tendency remains after the EOS correction, LBD is expected to be stronger than EOS in all three cases.

Fig. 11

The learning curve is modeled as a power law, as presented in equation (3) [33]. In this equation, C_t and $X_{cum,t}$ are the equipment cost and cumulative installed capacity at time t, respectively. C_0 and $X_{cum,0}$ are the values for the initial time *t=0*. The learning index α can be estimated from historical data. The progress rate (*PR*) and the learning rate (*LR*) are calculated using equations (4) and (5), where *LR* represents the cost reduction percentage when cumulative capacity is doubled.

$$C_t = C_0 \left(\frac{X_{cum,t}}{X_{cum,0}}\right)^{-\alpha} \quad (3)$$

$$PR = 2^{-\alpha} \quad (4)$$

$$LR = 1 - 2^{-\alpha} \quad (5)$$

We estimated the *LR* using standard OLS method for the total data and for each capacity category individually. We used the X_{cum} curves presented in Fig. 3, and the scale-corrected costs. Moreover, we performed a sensitivity analysis for the scale parameter, using the total average value of λ calculated in the previous section with an interval variation of ±50%. This interval covers the variations observed in the EOS analysis.

Regression analysis shows that the LR varies between 13.2 – 18.4% for the total equipment data, with R^2 lower than 0.3. Thus, the existence of LBD for SHP equipment costs in general cannot be confirmed. The individual analysis for capacity categories, however, depicts a better correlation. Fig. 12 presents the learning curves for mini and small plants, and Table 4 shows the result of the sensitivity analysis. We found a LR of 21±0.5% and 24±3% for mini and small plants respectively with acceptable adjustments ($R^2 \cong 0.7$) and statistical significance in the LR parameter (p-value < 0.1). These results show that small and mini hydropower plants in Colombia have experienced a LBD phenomenon, and that the learning process has produced a reduction in equipment costs of about 21-

24% after the cumulative installed capacity has doubled. The cumulative installed capacity of micro plants covers only one order of magnitude increase, and the data points are very close to each other in the log-log scale, which prohibits to derive a statistically significant learning curve for this category.

Fig. 12

Table 4

Our results are consistent with other RET studies, which report values of LR of around 20% for most technologies [33–36]. The sensitivity analysis for the scale parameter shows variations lower than 4% in R^2, and variations in LR from 20.5% to 26.6% (see Table 4). Hence, the assumed value for the scale parameter does not affect the final conclusion about the existence of a LBD phenomenon.

6. Discussion, limitations and conclusions

SHP is a mature technology in Colombia with more than a century of practical experience. Since the installation of the first plant in 1900, more than 200 plants have been built to electrify different regions in the country. The renewed interest of the government and private sector to install new SHP stations has increased over recent decades, given Colombia's hydropower potential and the limited social and environmental impacts of SHP. Different programs for electrification with SHP are currently running, which necessitates the analysis of the prospects for SHP in Colombia. In this paper we presented an investigation of the cost reductions for SHP, based on an inspection of both learning-by-doing and economies-of-scale effects.

We built a database of SHP plants installed in Colombia between 1900 and 2013, with information on capacity, year of installation, location, current state, and investment costs. The plants were classified in three categories, as micro plants (IC < 0.1 MW), mini plants (0.1 < IC < 1 MW), and small plants (1 < IC < 20 MW). Total costs were sub-divided into equipment, infrastructure, and other costs. We estimated a scale parameter on the basis of historical data including all three capacity categories. For our LBD analysis, we considered only mini and small SHP plants. We corrected the effects of EOS to a reference capacity, and thereby estimated the learning rate.

Our results suggest that infrastructure and total costs are mainly affected by EOS. For these cost measures we did not observe LBD. For equipment costs our results show that both EOS and LBD mechanisms have driven down the costs of SHP plants in Colombia. We found that equipment costs for mini and small SHP plants have declined with a learning rate of around 22%. More specifically, we found learning rates for equipment costs of 21±0.5% for mini plants, and 24±3% for small plants. Although the data set we used is limited, our statistical analysis showed that both the scale and the learning parameters are significant at a 90% confidence level. Future research could extend our database, whereby our results can be updated and validated with more information. Our sensitivity analysis showed that the value we calculated for the scale parameter does not affect our final conclusion about the existence of a LBD effect.

Although our LBD analysis was made with a relative large number of data for capacity (194 entries), our costs database was still relatively limited[13]. The limitation in the cost data that we gathered

[13] We collected 58 data points for total cost, 49 for infrastructure, 50 for equipment, and 39 for other costs. After excluding the data for non-connected areas, for our EOS analysis we ended up using 37 data points for total costs, 31 for infrastructure,

constitutes a source of uncertainty in our EOS and LBD estimations. Still, however, our analysis showed that both EOS and LBD parameters are statistically significant, which suggests that EOS and LBD phenomena do exist. During our study we made an effort to collect, organize, and report all the techno-economic data available for SHP in Colombia, whereby we built a database that was inexistent in the country before our work was initiated. The results reported in this article hopefully motivate other researchers to improve and extend this database, on the basis of which they could perform a more complete analysis in the future, and validate our present findings.

We recommend both public and private sectors to exploit the EOS and LBD mechanisms described in this study. More specifically, we recommend future private owners of SHP plants to join wherever feasible with neighboring co-owners. This allows exploiting the effects of EOS, and thus lowering relative investment costs. We thus advise to invest in relatively large SHP plants that can electrify, for example, a group of farms, rather than individual ones. The mechanism of EOS can also support a decline in operational costs, such that owners of existing plants can reduce costs by allowing plants to be operated by the same agent, as shown in [22]. Finally, we recommend that the implications of our work as applied to Colombia are inspected for other countries as well, not only in the direct vicinity on the South American continent where similar physical and/or socio-economic circumstances may hold (such as in Argentina, Bolivia, Chile, Ecuador, and Peru), but also in other (notably developing) regions across the world, notably Africa and Asia.

Acknowledgements

The analysis that allowed the publication of this paper was funded by the Enlaza Mundos program of the Colombian government (call 2013). Additional funding derived from the CLIMACAP project (European Commission, FP7/2011-2014), and the Colombian project “Impact of Distributed Generation (DG) on the National Transmission System”, funded by Interconexión Eléctrica S.A (ISA). The opinions expressed in this article are the sole responsibility of the authors. We would like to thank four anonymous reviewers for their critical comments that contributed substantially to the improvement of our analysis and paper. BvdZ also acknowledges support from the TRANSRISK project (European Commission, Horizon 2020, grant agreement No. 642260).

Conflict of interest

No conflict of interest.

References

[1] IPCC - Intergovernmental Panel on Climate Change, Final draft of Technical Summary, in: Clim. Chang. 2014 Impacts, Adapt. Vulverability - Contrib. Work. Gr. II to Fifth Assess. Rep., 2014: pp. 1–76.

[2] IPCC - Intergovernmental Panel on Climate Change, Final draft of Technical Summary, in: Clim. Chang. 2014 Mitig. Clim. Chang. - Contrib. Work. Gr. III to Fifth Assess. Rep., 2014.

[3] UN, Sustainable Energy for All - A Framework for Action, United Nat, United Nations, The Secretary-General’s High-level Group on Sustainable Energy for All, New York, 2012.

[4] OLADE - Organización Latinoamericana de Energía, Potencial de Recursos Energéticos y

and 31 for equipment (the 21 data points for other costs were excluded from our analysis). For our LBD analysis, we considered only equipment costs, classified in 11 data points for micro, 7 for mini, and 13 for small SHP plants.

Minerales en América del Sur: Coincidencias Jurídicas hacia una Estrategia Regional, Quito, Ecuador, 2013.

[5] IEA - International Energy Agency, Renewable Energy Outlook, Paris, France, 2013.

[6] L. Pinguelli Rosa, M. Aurelio, D.O.S. Santos, B. Matvienko, E. Oliveira, E. Sikar, Greenhouse Gas Emissions from Hydroelectric Reservoirs in Tropical Regions, Clim. Change. 66 (2004) 9–21.

[7] J.P. Ometto, A.C.P. Cimbleris, M. a. dos Santos, L.P. Rosa, D. Abe, J.G. Tundisi, et al., Carbon emission as a function of energy generation in hydroelectric reservoirs in Brazilian dry tropical biome, Energy Policy. 58 (2013) 109–116. doi:10.1016/j.enpol.2013.02.041.

[8] L. Yang, F. Lu, X. Wang, Measuring Greenhouse Gas Emissions From China ' s Reservoirs, EOS, Trans. Am. Geophisical Union. 95 (2014) 2012–2014. doi:10.1029/2007GL029479.Kemenes.

[9] XM, Informe de Operación del SIN y Administración del Mercado, XM Filial de ISA, Medellín, Colombia, 2015.

[10] Unidad de Planeación Minero Energética, Registro de Proyectos de Generación, 1 (2014).

[11] Empresa de Energía de Bogotá, Universidad Externado de Colombia, Historia de la Empresa de Energía de Bogotá, Primera Ed, Empresa de Energía de Bogotá, Bogotá D.C., Colombia, 1999.

[12] INEA - Instituto de Ciencias Nucleares y Energías Alternativas, Guía de Diseño para Pequeñas Centrales Hidroeléctricas, Bogotá D.C., Colombia, 1997.

[13] E.R. Larsen, I. Dyner, L. Bedoya V, C.J. Franco, Lessons from deregulation in Colombia: successes, failures and the way ahead, Energy Policy. 32 (2004) 1767–1780. doi:10.1016/S0301-4215(03)00167-8.

[14] S. Arango, I. Dyner, E.R. Larsen, Lessons from deregulation: Understanding electricity markets in South America, Util. Policy. 14 (2006) 196–207. doi:10.1016/j.jup.2006.02.001.

[15] Congreso de la República de Colombia, Ley 143 de 1994 - Ley Eléctrica, Congreso de la República, Bogotá D.C., Colombia, 1994.

[16] IRENA - International Renewable Energy Agency, Renewable Energy Technologies: Cost Analysis Series - Hydropower, Bonn, Germany, 2012.

[17] Unidad de Planeación Minero Energética, Costos Indicativos de Generación Eléctrica en Colombia, Bogotá D.C., Colombia, 2005.

[18] K. Schoots, F. Ferioli, G. Kramer, B. Van der Zwaan, Learning curves for hydrogen production technology: An assessment of observed cost reductions, Int. J. Hydrogen Energy. 33 (2008) 2630–2645. doi:10.1016/j.ijhydene.2008.03.011.

[19] G.J. Stigler, The Economies of Scale, J. Law Econ. 1 (1958) 54–71.

[20] M. Nerlove, Returns to Scale in Electricity Supply, in: C.F. Christ (Ed.), Meas. Econ. Stud. Math. Econ. Econom. Mem. Yehuda Grunfeld, Stanford University Press, California, 1963.

[21] L.R. Christensen, W.H. Greene, Economies of Scale in U.S. Electric Power Generation, J. Polit. Econ. 84 (1976) 655–676.

[22] M. Filippini, C. Luchsinger, Economies of scale in the Swiss hydropower sector, Appl. Econ. Lett. 14 (2007) 1109–1113. doi:10.1080/13504850500438728.

[23] E.B. Hreinsson, Economies of Scale and Optimal Selection of Hydroelectric Projects, in: Int. Conf. Electr. Util. Deregul. Restructring Power Technol., London, 2000: pp. 284–289.

[24] L. Kosnik, The potential for small scale hydropower development in the US, Energy Policy. 38 (2010) 5512–5519. doi:10.1016/j.enpol.2010.04.049.

[25] S. Mishra, S.K. Singal, D.K. Khatod, Cost Analysis for Electromechanical Equipment in Small Hydropower Projects, Int. J. Green Energy. 10 (2013) 835–847. doi:10.1080/15435075.2012.727367.

[26] Q.F. Zhang, B. Smith, W. Zhang, Small Hydropower Cost Reference Model, Tennessee, 2012.

[27] G. a. Aggidis, E. Luchinskaya, R. Rothschild, D.C. Howard, The costs of small-scale hydro power production: Impact on the development of existing potential, Renew. Energy. 35 (2010) 2632–2638. doi:10.1016/j.renene.2010.04.008.

[28] K.J. Arrow, The Economic Implications of Learning by Doing, Rev. Econ. Stud. 29 (1962) 155–173.

[29] F. Ferioli, K. Schoots, B.C.C. van der Zwaan, Use and limitations of learning curves for energy

technology policy: A component-learning hypothesis, Energy Policy. 37 (2009) 2525–2535. doi:10.1016/j.enpol.2008.10.043.

[30] A.D. Sagar, B. van der Zwaan, Technological innovation in the energy sector: R&D, deployment, and learning-by-doing, Energy Policy. 34 (2006) 2601–2608. doi:10.1016/j.enpol.2005.04.012.

[31] A. van Benthem, K. Gillingham, J. Sweeney, Learning-by-Doing and the Optimal Solar Policy in California, Energy J. 29 (2008) 131–151.

[32] T. Jamasb, J. Köhler, Learning Curves for Energy Technology : A Critical Assessment, in: M. Grubb, T. Jamasb, M.G. Pollitt (Eds.), Deliv. a Low Carbon Electr. Syst. Technol. Econ. Policy, Cambridge University Press, Cambridge, 2007.

[33] International Energy Agency, Organisation for Economic Co-operation and Development, Experience Curves for Energy Technology Policy, IEA Publications, Paris, France, 2000.

[34] Å. Lindman, P. Söderholm, Wind power learning rates: A conceptual review and meta-analysis, Energy Econ. 34 (2012) 754–761. doi:10.1016/j.eneco.2011.05.007.

[35] A. McDonald, L. Schrattenholzer, Learning rates for energy technologies, Energy Policy. 29 (2001) 255–261. doi:10.1016/S0301-4215(00)00122-1.

[36] K. Schoots, G.J. Kramer, B.C.C. van der Zwaan, Technology learning for fuel cells: An assessment of past and potential cost reductions, Energy Policy. 38 (2010) 2887–2897. doi:10.1016/j.enpol.2010.01.022.

[37] National Oceanic and Atmospheric Administration, What are El Niño and La Niña?, Ocean Facts. (2014). http://oceanservice.noaa.gov/facts/ninonina.html (accessed August 26, 2014).

[38] Congreso de la República de Colombia, Ley 855 de 2003, Congreso de la República de Colombia, Bogotá D.C., Colombia, 2003.

[39] Banco de la República, Informe sobre Inflación, Bogotá D.C., Colombia, 2012.

[40] United States Bureau of Labor Statistics, Inflation and Prices, (2013).

Table 1 Classification of plant capacity (x) of SHP in this study

Category	Plant Capacity [MW]
Small hydropower	$1.0 < x \leq 20$
Mini hydropower	$0.1 < x \leq 1.0$
Micro hydropower	$x \leq 0.1$

Table 2 Scale parameter estimated for SHP in Colombia

Period		Years	Equipment			Infrastructure			Total		
			1- λ	R^2	t*	1- λ	R^2	t*	1- λ	R^2	t*
1985 -	1990	5	0.08	1.0	8.99	0.11	0.5	1.77	0.06	0.6	2.02
1990 -	1995	5	0.06	0.7	3.42						
1990 -	2000	10				0.44	0.9	8.26	0.12	0.5	3.18
1995 -	2010	15	0.15	0.3	1.01						
2000 -	2013	13				0.35	0.7	2.77	0.35	0.7	2.77
2010 -	2013	3	0.47	0.8	2.58						
Average (R^2>0.7)			**0.200**			**0.393**			**0.346**		

*The highlighted results have a t value greater than the critical t value, and are significant with a confidence of 90%

Table 3 Values of (1-λ) for SHP abroad

Source	Equipment	Infrastructure	Total
[25]	0.182 – 0.190	0.240 – 0.376	
[26]	0.287		0.300 – 0.350
[27]			0.350 – 0.400
[23]			0.220
Average abroad	0.236	0.311	0.307
Average Colombia	0.200	0.393	0.346
Total average	0.218	0.352	0.326

Table 4 Sensitivity analysis for scale parameter

(1-λ)	Mini plants			Small plants		
	- α	LR	R^2	- α	LR	R^2
Av. -50%	-0.331	20.5%	0.7	-0.447	26.6%	0.7
Average	-0.340	21.0%	0.7	-0.391	23.7%	0.7
Av. +50%	-0.349	21.5%	0.7	-0.336	20.8%	0.6

All values are statistically significant under a *t*-test analysis, with a confidence of 90%

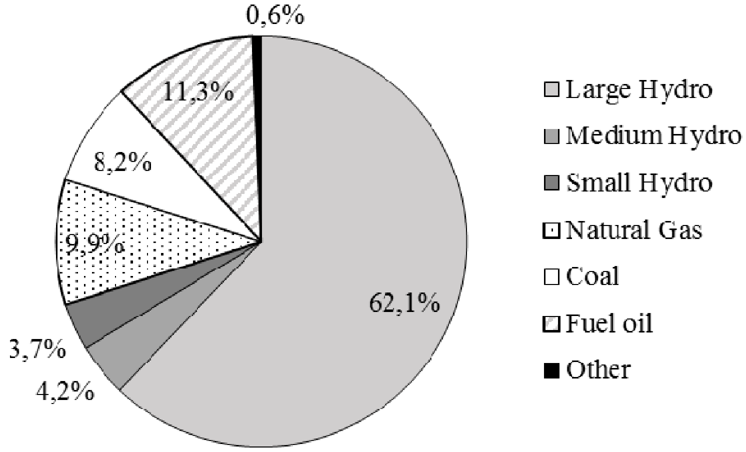


Fig. 1 Composition of installed electricity generation capacity in Colombia in 2015. Based on [9]

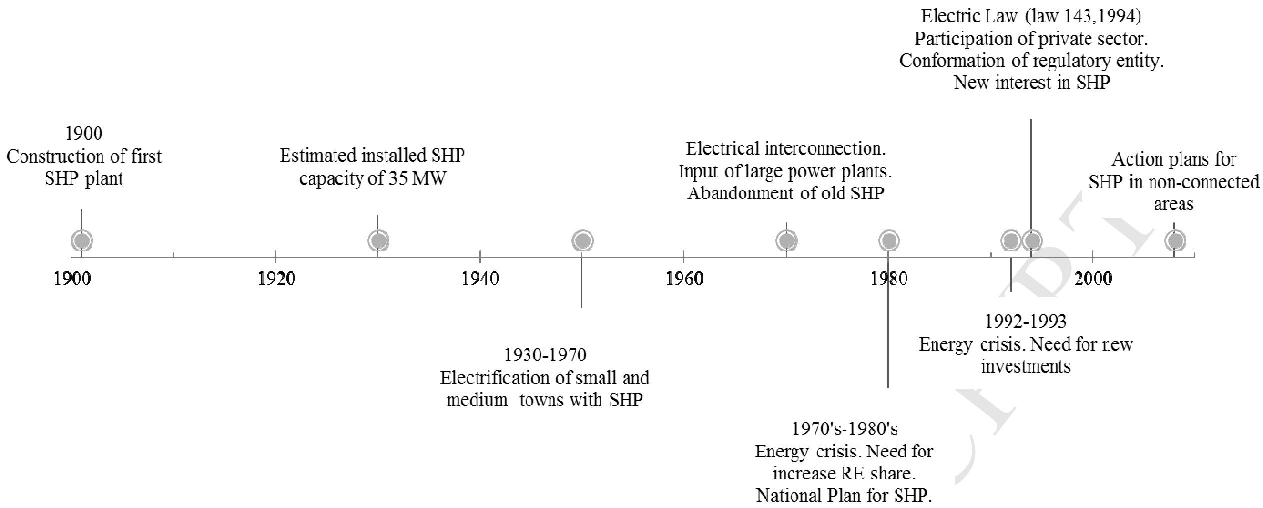


Fig. 2 Timeline of the development of Small Hydropower in Colombia

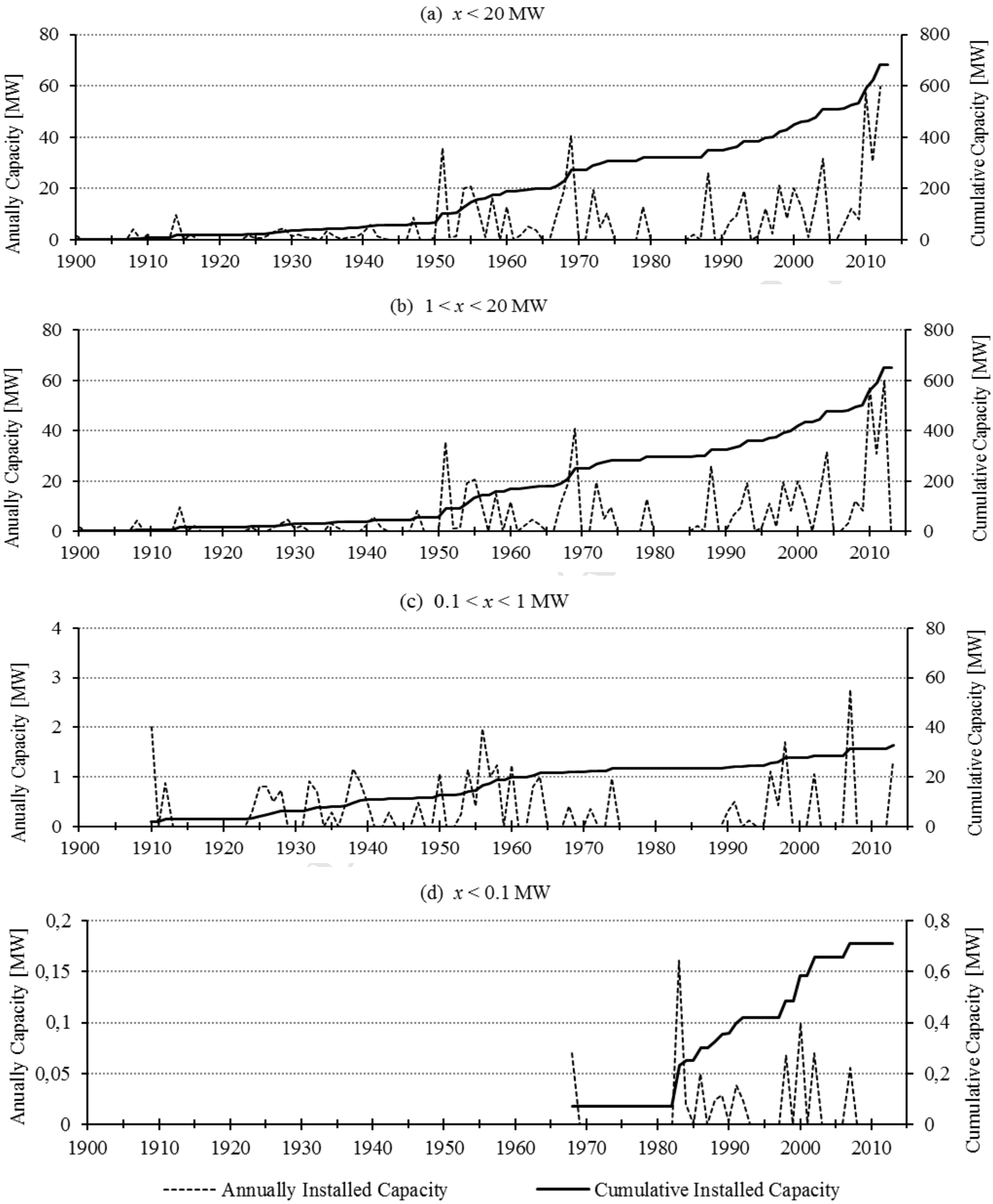


Fig. 3 Evolution of annually installed capacity and cumulative installed capacity of SHP plants in Colombia by capacity category

(Database comprises 191 plants: 21 micro plants, 67 mini plants, 103 small plants)

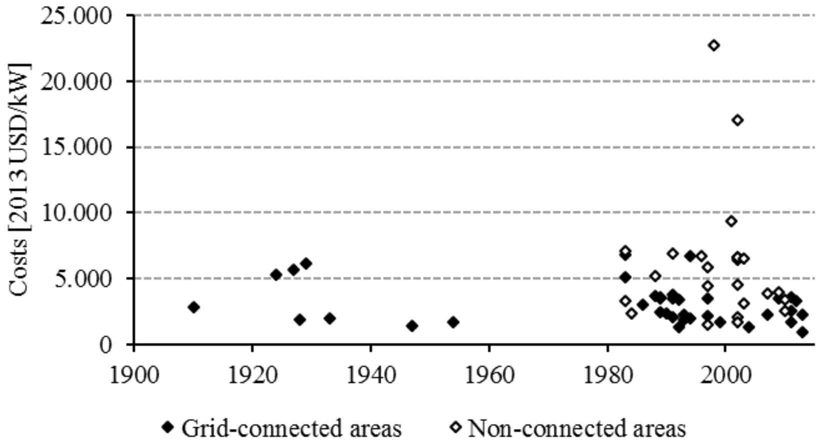


Fig. 4 Historical investment costs for SHP in Colombia distinguished into installations in grid-connected and non-connected areas

(52 data points: 15 for non-connected and 37 for grid-connected)

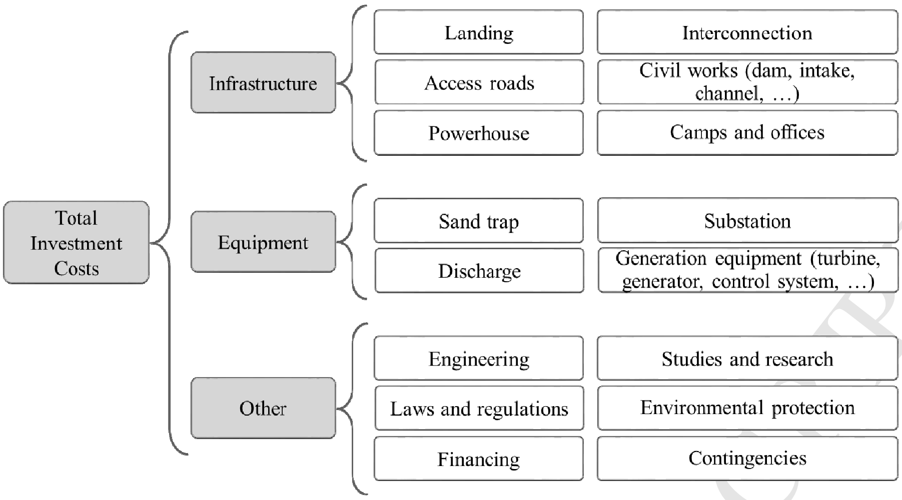


Fig. 5 Cost breakdown for SHP (based on [17])

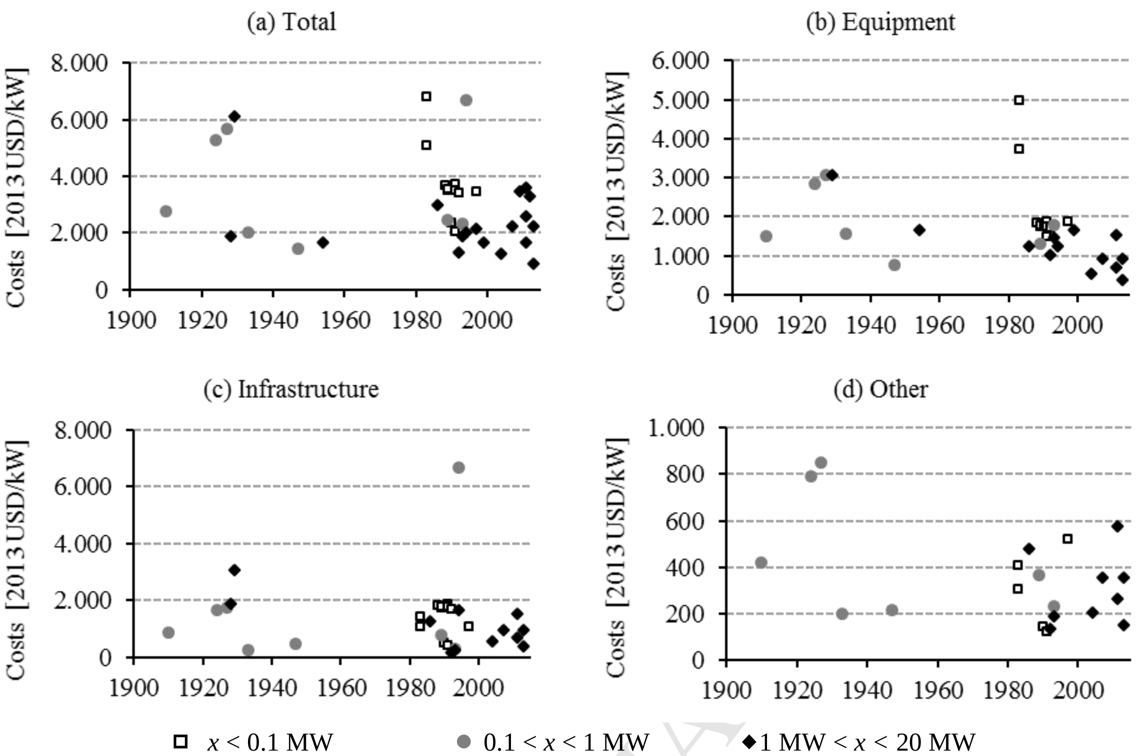


Fig .6 Investment costs for SHP for grid-connected areas in Colombia by cost type and capacity category

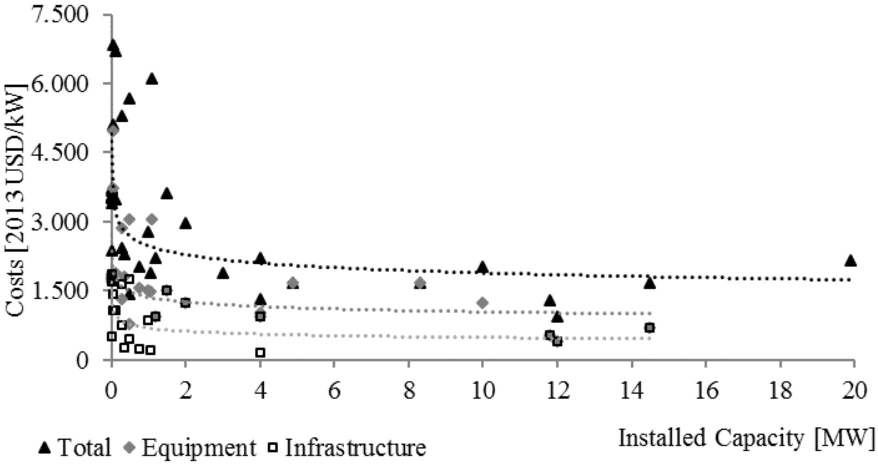


Fig. 7 Economies of scale for SHP investment costs in Colombia
(37 data points for total costs, 31 data for equipment, and 31 data for infrastructure)

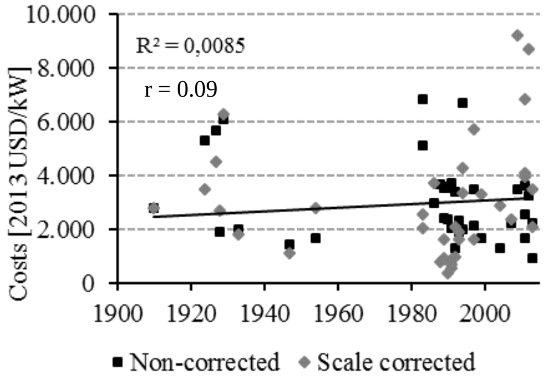


Fig. 8 Scale correction for total costs

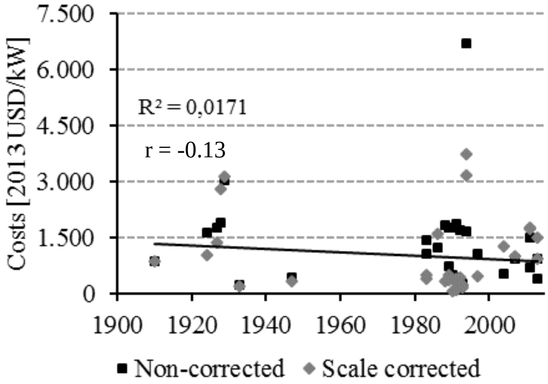


Fig. 9 Scale correction for infrastructure costs

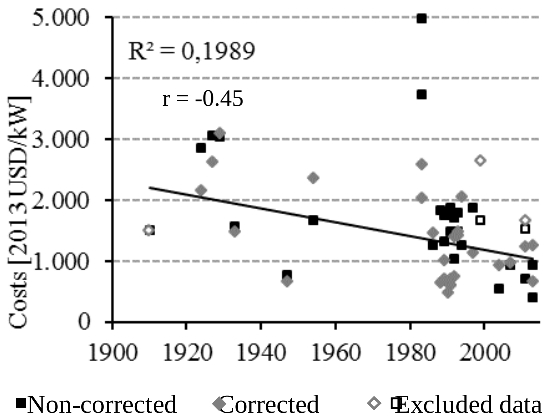


Fig. 10 Scale correction for equipment costs

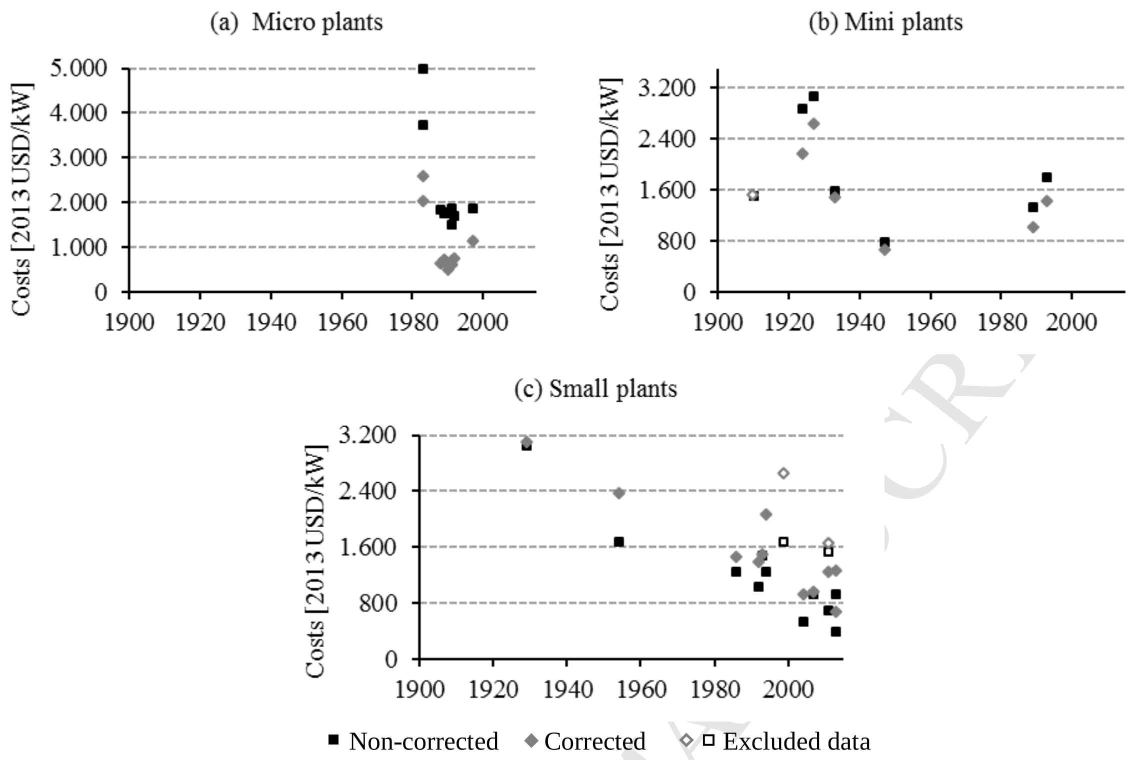


Fig. 11 Scale correction for equipment costs by categories of SHP

(31 data for equipment costs: 11 for micro plants, 7 for mini plants, and 13 for small plants)

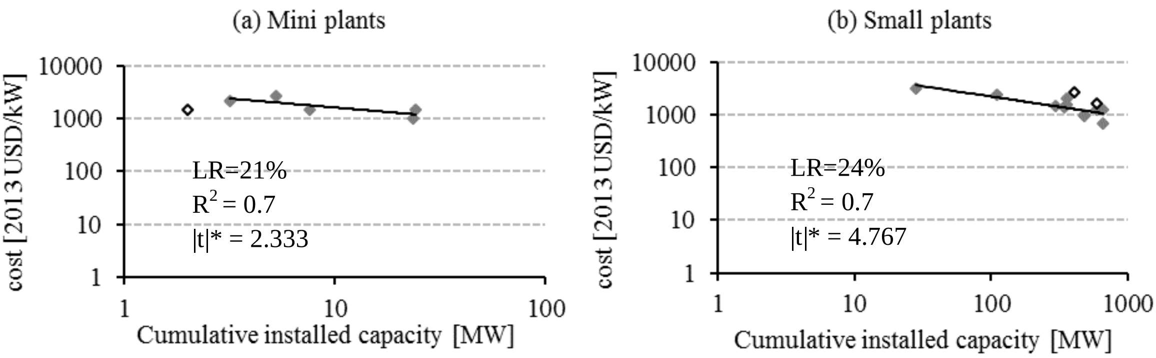


Fig.12 Learning curves for equipment costs of Mini and Small hydropower plants

*Both t values are greater than the critical t value, with a confidence of 90%

Highlights

- We inspect the costs trend for Small Hydropower(SHP) in Colombia from 1900 to 2013
- Learning-by-doing (LBD) and Economies-of-scale (EOS) have decreased the costs of SHP
- LBD affects mainly the equipment costs, EOS affects infrastructure and total costs
- We found an average learning rate of 21% for equipment costs