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Incentives for wind power investment in Colombia

Javier Contreras [a], Yeny E. Rodríguez [b, *]

[a] University of Castilla-La Mancha, E.T.S. de Ingenieros Industriales, 13071 Ciudad Real, Spain
[b] ICESI University, Financial and Accounting Department, Cali, Colombia

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ABSTRACT

This paper develops an energy policy measure for renewable sources in Colombia, in particular wind generation. The proposal is done at the decentralized level, in isolated areas of the country, where electricity coverage is below 12% and wind speed is suitable for power generation. The goal of this policy is focused on increasing electricity coverage in those remote areas of the country that have high winds in order to develop clean generation investments that can represent a benefit for low-income users. Thus, a mechanism for financing these kinds of investments is proposed, involving the private sector and using the mechanism known as Public Private Partnerships – PPPs. PPPs are mechanisms used by the public sector to establish a contract with the private sector. The private sector provides capital and ability to develop projects, while the public sector holds the responsibility in service delivery. To model the relationship between public sector and private investors, a bilevel programming method for efficient resource allocation, combining an auction mechanism and moral hazard, is presented. A case study is shown in the Colombian context.

1. Introduction

The development of new technologies and fuel price uncertainty have motivated the search for an energy portfolio of minimum cost and risk, to improve energy security and reduce CO_2 emissions. These energy portfolios include the participation of renewable sources as stated by Refs. [4] and [32]. Among the fastest growing renewable technologies worldwide, wind is prevalent. In 2012 wind power capacity in the world increased by 45 GW, for a total of 282 GW installed. Wind power electricity production accounted for 2.5% of the global electricity demand (IEA, 2013).

In literature, the discussion of the biggest share of renewables in the energy mix has focused on measures to define an acceptable penetration level and determine regulatory instruments to encourage their use. The number of countries that had some type of policy to promote the use of renewable energy increased from 48 in 2005 to 109 in 2012. This was motivated primarily to reduce CO_2 emissions and dependence on fossil fuels [22].

The Latin American case is different. Few countries (Chile, Argentina, Brazil, Peru, Mexico and Uruguay) have policy measures which promote the use of renewable energy [3]. In the particular case of wind energy, the absence of regulation and incentives and the abundance of resources, such as water and coal, stand out as major barriers to the development of this technology in Colombia [26].

Regarding how to implement policy measures that promote renewable energies in an effective way, the two most important factors are: i) definition of clear policies by governments and ii) regulatory stability for market participants (investors and utilities) [22]. However, it must be noted that the use of renewable energies, in particular wind energy, will not reduce the need for conventional power plants. This is because the demand for electricity is continuous, and wind power is intermittent and more expensive to produce most of the time, making it difficult to store on a large scale. Also, according to [33]; electrical system integration of intermittent power at levels of penetration below 5% does not have a significant impact on system reliability.

1.1. Electricity generation in Colombia

In Colombia, the market architecture is centralized and is characterized for having a market operator (XM) responsible for managing market bids and subject to the technical constraints of the system.

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* Corresponding author.
E-mail addresses: Javier.Contreras@uclm.es (J. Contreras), yerodriguez@icesi.edu.co (Y.E. Rodríguez).

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In December 2012 the generation resources that were connected to the National Interconnected System (NIS) had a hydraulic capacity share of 63.65%, followed by thermal (31.43%), and other minor sources, with a share of 4.92%. In particular, wind power represented 0.15% of the installed capacity [40]. These figures reflect the emerging use of non-conventional energy sources (NCES) in Colombia and their lack of diversification of energy sources.

Regarding costs, wind technology costs are higher than the ones of conventional technologies [15] and [16], however, in some isolated areas of Colombia the most abundant resource is wind.

In Colombia, the efforts to define a policy and regulatory incentives by Congress have been focused on defining different mechanisms such as FAZNI (Fondo de Apoyo Financiero para la Energización de las Zonas No Interconectadas), FAER (Fondo de Apoyo Financiero para la Energización de las Zonas Rurales Interconectadas), PROURE (Programa de uso racional y eficiente de energía y otras fuentes no convencionales de energía), tax exemptions and reliability charges. In spite of the existence of these funds there is no definition of promotion mechanisms to achieve these goals.

1.2. Literature review of mechanisms to encourage the use of renewable energy

Mechanisms to promote the use of renewable energy gained close attention in the power sector, a detailed literature review is presented in Ref. [27] According to these authors the mechanisms can be classified into price- and quantity-based.

1.2.1. Mechanisms based on prices

Public authorities manage prices when offering subsidies to encourage activities that are valuable from a public perspective but not adequately supported by consumer demand [41]. Mechanisms based on prices provide economic incentives, which can be given in the form of extra payments or guaranteed rates (Feed in Tariff – FiT), guaranteed premiums (Feed in premium – FiP), tax incentives, investment and financing incentives, exemptions of fees, and allocation of subsidies in a competitive way.

FiT guarantees a specific price for each kWh that is generated from renewable energy, including subsidies. This mechanism is guaranteed from 10 to 30 years, and the amount may depend on technology, plant size or capacity factor [27].

FiP consists of a guaranteed payment to renewable generators in the form of premiums or bonds that are above existing electricity market prices [24], which changes with the time. Similar to FiT, this is a long-term payment as well and the premium may depend on the facility characteristics [27].

Tax incentives are options used by governments in order to reduce the cost of financing from investors. The ones which have been widely used are: i) accelerated depreciation, ii) fuel taxes, and iii) tax exemptions.

Investment subsidies have been granted to renewable energy technologies, offering down payments that depend on the total installed capacity.

Financing incentives refer to loan programs with interest rates below the rates that are used in the market.

Payment exemptions have been implemented in markets where the fee is disaggregated.

1.2.2. Mechanisms based on quantities

The purpose of mechanisms based on quantities is to increase the production of energy from renewable sources. The two basic types of quantity mechanisms are: tradable green certificates and renewable energy auctions [27].

Tradable green certificates work as tradable quotas, which are set by the regulator, who establishes which agents have to meet renewable energy commitments. These commitments are represented by certificates of purchase or production of renewable energy. These certificates can be traded in a secondary market, and they are usually awarded per unit of electricity produced with renewable sources. The agents that participate in the certificate market may buy certificates from renewable producers, where a penalty must be paid in case of non-compliance, which represents the maximum cost of the certificate. Sometimes, a minimum cost is established in order to guarantee the profitability of renewable facilities [27].

Auctions are other quantity-based mechanisms but with some of the advantages of price-based mechanisms, therefore, it is halfway between these two mechanisms [27]. Renewable energy auctions are defined by the regulator, who establishes a demand for a certain technology and sets up the price and volume to meet the demand. The regulator guarantees the winner the price reached in the auction through a long-term contract [27]. In this way, long-term contracts can make the expansion in generation relevant and sustainable [7].

1.2.3. Comparison of mechanisms

In developed countries, price-based mechanisms dominate in order to encourage the use of renewable energy. In this case, FiT prevails, presenting lower costs compared to FiP [37] and [30]. This approach has been unsuccessfully used in South America.

Other mechanisms that have been used for promoting renewables are the auctions applied in Brazil, Argentina, Peru, Uruguay, Ontario (Canada) and California (USA), and financing incentives granted by multilateral agencies in countries like Chile and Brazil [2]. The use of tax incentives has been less frequent in countries like the United States, Finland and China [28], but they are present in several countries (also in Colombia and other Latin American countries) and are used in parallel with other schemes.

The quantity-based mechanism has been used by few developed countries (United Kingdom, Italy, Sweden, Belgium, Poland and Romania) and by few South American countries, in particular Chile [41].

Currently, developed countries are offering FiT schemes combined with auctions to support less mature renewable technologies or small-scale renewable projects [6].

1.3. Literature review on allocation of investment projects

When the government requires an infrastructure project, it usually sets a bidding process, inviting interested firms to make offers and selects the one with the lowest bid.

In this process, information asymmetries are observed, leading to problems of adverse selection and moral hazard. The adverse selection problem arises when the government does not know the expected cost of any firm. Moral hazard arises from the fact that the government cannot observe the ex-post effort of the selected firm that allows them to keep low production costs.

The government must design a contract to control these two problems, which would not exist if the principal (government) and the agents (firms) had the same objective function.

In literature [25], model an optimal contract between the government and a firm that makes a project for the government, assuming that both parties are risk neutral and the government has problems of adverse selection and moral hazard. The optimal strategy is obtained with an incentive contract consisting of a fixed payment, a linear announced cost and the existence of project overruns.

When there are firms that are possible candidates for a project

[13], has argued that the best mechanism to generate competition is through an auction. Thus [29], model an optimal contract between the government and several firms competing for it under moral hazard, for which all these authors suggest using participation constraints and incentive compatibility to solve the moral hazard problem. This is because an agent is involved in the offer to the extent that the expected utility of its profit is positive, and the agent chooses an effort level that maximizes their expected ex-post utility.

The authors show that the optimal contract is determined by the tradeoff between two factors: i) stimulating competition among competitors and risk sharing between the government and contractors, and ii) giving the contractor incentives to limit their production costs.

The aim of our work is to identify feasible policy measures to encourage the use of renewable energies, such as wind, taking into account the structure of the Colombian electricity market (also applicable to other markets). The proposed policy measures are developed in areas that do not have connections with the National Grid. These measures involve: i) to define the type of mechanism, ii) to allocate funding sources efficiently to qualified operators to supply power if their costs are not competitive in the short term, and iii) to establish the percentage of participation in the energy mix of the country.

The rest of the paper is organized in four parts. The second part presents the bilevel programming methodology proposed, containing the objectives at the decentralized level that support the decision of the mechanism chosen, and describes the proposed policy, the sources of funding and a method for investment allocation. Additionally, this part presents the percentage of participation of wind generation in isolated areas of Colombia. The third part presents the results and a discussion of a case study regarding the investment allocation mechanism in remote areas, taking into account moral hazard of the project developers. Finally, we present conclusions and policy implications.

2. Proposed methodology

2.1. Investment incentives in wind energy

In Colombia, 33% of the country's area has power transmission lines that are interconnected within the National Interconnected System – NIS (central level). The geographic areas whose energy demand is not served by NIS are called Non-Interconnected Areas – NIA (decentralized level).

The geographical area belonging to NIA is served through a generation mix with an installed capacity (214,000 kW) which is equal to 1.6% of the country's total installed capacity. The population density of NIA is low, there are approximately 1.3 million people (2.7% of the country's population), from which 63% have electricity service for an average of 5.3 h per day [39].

In order to define mechanisms for promoting wind energy, the government's objectives are different depending on the level. At the centralized level, the government is interested in increasing the country's energy security, reducing congestion in the transmission and distribution networks (Action Plan 2010–2015). At the decentralized level, the core objectives are: i) to increase electricity coverage in remote areas of the country where there is enough wind, and ii) to invest in clean generation resources that benefit low-income users (Action Plan 2010–2015).

2.2. Policy definition

In this paper we describe policy measures at the decentralized level to encourage the use of wind energy in rural areas of Colombia taking into account different sizes of wind turbines. A mechanism to get funding to make investments and an allocation mechanism based on auctions, involving moral hazard of investors, are proposed.

It is proposed that investment incentives are defined in two scales: small (capacity less than 20 kW) and medium (capacity between 20 kW and 1000 kW). Small wind turbines will be installed in isolated areas with strong winds that have no electrical service, and medium-sized wind turbines will be installed in isolated areas with strong winds where provision of electricity service is generated through diesel generation plants. Differentiation is made according to the scale because they have different criteria to meet the objectives, defining the participation of wind energy. The policy measure refers to small wind generators that can either act in an independent way or jointly, forming micro-networks. Although the model is theoretical, in this paper we present an applied case using this methodology.

2.2.1. Small-scale projects

On a small scale, according to Action Plan 2010–2015, the government wishes to improve the quality of life of the population that does not have electricity service and, therefore, the parameter used to define the wind capacity required is electricity coverage. It is proposed that autonomous systems are installed in isolated areas in the rural municipalities of La Guajira (Dibulla, Manaure and Uribia) so that electricity coverage will be 16.4% in 10 years.

It is estimated that 46,801 users in rural areas of these municipalities do not have electricity service [17]. With this policy it is expected that electric service to 7636 users would be provided in 2024. This would require installing small wind turbines with a total estimated capacity of 46,000 kW. The calculation is performed under the assumption that these areas are purely residential, which equals the average consumption of a residential user in NIA (207.24 kWh-month/user) according to Sistema Único de Información (SUI), and whose installation will be done gradually: 4600 kW each year.

2.2.2. Medium-scale projects

On a medium scale, the government's desire is to decrease dependence on fossil fuels in isolated areas that predominantly use diesel generators. In this way, wind energy will be used as a source for additional generation. The criterion to estimate the wind capacity to be installed will be based on the diesel generation capacity installed: tripling the diesel capacity. This takes into account that the wind utilization factor of a wind plant is low, between 25% and 30% Ref. [35] and [10].

It is proposed that these medium-sized solutions are installed in coastal municipalities of Cauca (Guapi, and Timbiqui Micay López) and Nariño (El Charco, the Tola, Mosquera, Olaya Herrera, Pizarro and Santa Bárbara). These are municipalities with feasibility for installation of this technology. Currently they have electric power generation with diesel plants with a nominal capacity of approximately 25,000 kW (9000 kW to 16,000 kW in Cauca and Nariño) and have developed their own distribution networks [39]. Therefore, the total installed wind capacity will be 75,000 kW.

2.3. Sources of funding

The proposed policy involves the installation of wind turbines with a total capacity of 121,000 kW in the decade from 2014 to 2024, in areas without electric service, which would accumulate a total wind installed capacity of 147,500 kW in isolated zones[1]. It is estimated that the total investment would be around $296,500M Colombian pesos (approximately US$ 157M), assuming a turbine installation cost equivalent to US$1,300/kW, as estimated from international experience [19–21], which shows variations in the installation cost per kW per country.

Before the 1980s, most of the projects were built and maintained with public funds, however, in the case of public services, the benefit of the private sector involvement in service provision has been attributed to the fact that the public sector must not compromise their own capital in financing [18]. Other benefits include: quality improvement, innovation, management efficiency and effectiveness [8]. New business models with private sector participation called Public–Private Partnerships – PPPs have emerged and are defined as: "… *innovative methods used by the public sector to contract with the private sector, who provides the capital and its ability to develop projects on time and on a budget, while the public sector retains responsibility for providing these services to the public in a form that benefits in order to achieve economic development and improved quality of life*." [18].

The application of PPPs varies between countries, mainly due to differences in: i) legal framework, ii) institutional arrangements, iii) level of political commitment, iv) level of experience, and v) contracting approaches [34].

The UK, Canada, Japan and Australia have programs under PPPs mostly focused on road infrastructure projects, while the United States has extensive experience with leasing programs in the provision of public services [8]. In Latin America, between 2005 and 2009, the region has maintained an increasing trend in investments through PPPs. In the 2000s the most concentrated sectors with PPP investment volumes were energy and transport in countries like Chile, Colombia and Peru [38].

Institutional investors can participate in non-conventional technology investments the same way as it is done in infrastructure projects through: i) debt financing of the project operators (green bonds), ii) equity investment in listed companies involved in renewable generation projects, iii) infrastructure fund investment companies (in companies listed or not), which focus on these infrastructure projects, and iv) direct investment in the equity of developers of such projects [12].

The proposal for Colombia is to finance small- and medium-scale wind investments in isolated areas through the issue of bonds, whose underlying assets will become wind power projects to be developed. It is proposed that the bond issue for wind projects will be carried out annually, amounting to approximately US$15.7M.

The government would be the issuer of the bonds for electric power projects with wind generation. The bonus would be with a coupon floating rate. The maturity of the bond would be 18 years, considering that wind projects have a lifetime of 20 years. The coupon rate would be set to be financially attractive (competitive interest rate) and secure (reliable guarantees) to institutional investors.

2.4. Allocation of wind investment in isolated areas

Once the government has the necessary capital to develop wind projects, it is proposed that it will hold a reverse auction to assign incentive contracts with project developers that are able to perform them, taking into account their moral hazards. In this kind of auctions the auctioneer is the buyer and the bidders are the sellers.

Reverse auctions have been used extensively in the telecommunications sector in rural areas in countries such as Australia, Chile, Colombia, India, Nepal and Peru. These auctions have provided universal service successfully, and have reduced the subsidies granted by the government substantially [7,42].

In our case, we choose to carry out a deterministic auction [5], whose solution can be found by linear programming methods.

We chose a first-price auction in a sealed envelope bearing in mind that this type of auction encourages entry, prevents collusion and avoids abusive behavior. However, weaker bidders, i.e., the ones that are not experts in the field, are those who are most likely to win the auction, since they submit bids very close to their marginal costs [23].

The definition of participation constraints and incentive compatibility, which model the moral hazard problem, is carried over from the certainty equivalent of the expected utility of the profit.

The amount payable to the winner of a first-price sealed-bid auction will be determined by an incentive contract, in which the government will participate in the costs of the investor with an optimal fraction. It is assumed that wind project developers are risk averse.

In this case, the result of the auction is the subsidy (in $/kWh) requested by wind project developers, representing the money that they are willing to accept for the installation, operation and maintenance of wind turbines. The period of construction of the turbines is 2 years maximum, which will be counted from the date of completion of the auction.

The auction number matches the number of bond issues, i.e., 10 auctions (one per year), in which the amount of the projects is around $15.7 million, including the installation of small and medium-sized turbines in the coastal municipalities of La Guajira, Cauca and Nariño.

The deterministic auction is planned as a bilevel principal-agent program, which captures the hierarchical interaction of decision makers (government and potential project developers).

It assumes the existence of two types of decision makers: i) a principal interested in promoting the use of renewables (government) and ii) n agents interested in developing wind projects in the country.

2.4.1. Conditions for the government

The government is risk-neutral and designs a linear incentive contract that minimizes the expected payment made to the agent.[2] This is an incentive-based contract defined as a linear combination of the winning bid and the total costs of the project developer winner:

$$P = (1-\alpha)b_j + \alpha c_j \tag{1}$$

The total costs of project developer j are disaggregated: $c_j = c_i^* + w - e_j$, where c_i^* represents the project's costs, w represents unforeseen costs, which follow a Normal distribution with zero mean and constant variance, σ^2, and e_j represents the effort of project developer j.

Under these conditions the regulator wishes to minimize the expected payoff that will make to investor j, the winner, so that:

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[1] Currently, two wind projects exist: Jepirachi wind park of 19,500 kW and a project in development located in San Andrés of 7500 kW.

[2] The government wants to decrease the percentage of participation, in order to expose the winner agent to the observable costs for making more effort and reducing costs.

$$\min_{0\le\alpha\le1}\mathbb{E}[P] = \mathrm{E}\left[(1-\alpha)b_j + \alpha c_j\right] = (1-\alpha)b_j + \alpha\left(c_j^* - e\right) \tag{2}$$

2.4.2. Conditions for project developers

There are n risk-averse wind project developers who are interested in maximizing the expected benefit resulting from the incentives contract. They present a moral hazard problem, since the effort made by them is not observable by the government. In this case, the effort of project developers can be viewed as a reduction in costs through the purchase of technology at competitive prices or finishing construction in less time.

The non-observability of the effort of project developers affects the subsidy that the government recognizes, so that the designed contract should induce developers to make a positive effort, for which they must satisfy an incentive constraint and participate voluntarily, where a standard participation constraint is imposed. Feasible incentive contracts are those that satisfy these two constraints.

The profit of wind developer j, π_j, is determined by:

$$\pi_j = (1-\alpha)b_j - (1-\alpha)\left(c_i^* + w - e_j\right) - h\left(e_j\right), \tag{3}$$

where b_j is the bid of developer j, c_j is the total cost of developer j and $h(e_j)$ is the cost function of the effort by developer j. It is assumed that the cost function is given by a quadratic function of the effort as: $h(e_j)$=$0.5\gamma e^2$, with γ being a positive coefficient of the cost effort.

The expected value and variance of the benefit of project developer j are:

$$E\left[\pi_j\right] = (1-\alpha)\left(b_j - c_j^* + e\right) - 0.5\gamma e^2, \tag{4}$$

$$Var\left[\pi_j\right] = (1-\alpha)^2\sigma^2 \tag{5}$$

The certainty equivalent of the benefit of project developer j, VC_j, is calculated as the expected value of the benefit minus the risk premium, the latter measure following the local Arrow-Pratt[3] risk premium measure. Therefore, the true equivalent benefit of the investor is determined by the following expression:

$$VC_j = (1-\alpha)\left(b_j - c_j^* + e_j\right) - 0.5\gamma e^2 - 0.5(1-\alpha)^2\sigma^2\rho \tag{6}$$

Under these conditions, each developer will be interested in maximizing their expected profit, subject to incentive compatibility and participation constraints.

The incentive compatibility constraint for each developer chooses the effort that maximizes the certainty equivalent of profit. This optimal effort can be obtained by taking the derivative of the certainty equivalent of the profit with respect to the effort.

This constraint can be expressed as $\frac{\partial VC_j}{\partial e_j} = 0$, which results in $e_j = \frac{(1-\alpha)}{\gamma}$. The effort is expressed in terms of cost and the level of government involvement.

The participation constraint is determined by the ratio between the certainty equivalent of the benefit of the project developer and the minimum benefit. The minimum benefit is denoted by $z_{0,}$ and defined at the $z_0 = 0$ level.

$$VC_j = (1-\alpha)\left(b_j - c_j^* + e\right) - 0.5\gamma e^2 - 0.5\rho(1-\alpha)^2\sigma^2 \ge z_0 \tag{7}$$

Thus the problem of project developer j is:

$$max_{b_j}\mathbb{E}\left[\pi_j\right] = \left((1-\alpha)\left(b_j - c_j^* + e\right) - 0.5\gamma e^2\right) \tag{8}$$

s.t.

$$b_j < h,\ with\ h = \min\left(b_{i-\{j\}}\right)i, j = 1, \ldots, n \tag{9}$$

$$e_j = \frac{(1-\alpha)}{\gamma}\quad (Incentive\ constraint) \tag{10}$$

$$(1-\alpha)\left(b_j - c_j^* + e\right) - 0.5\gamma e^2 - 0.5\rho(a-1)^2\sigma^2 \ge 0\quad (Participation\ constraint) \tag{11}$$

where $h = \min\left(b_{i-\{j\}}\right)$ is the minimum offer of all the bidders, excluding the j-th.

2.4.3. Bilevel principal-agent model

The hierarchical structure is a key issue in a bilevel model. In a first step, the government acts as leader and decides the level of participation in the contract incentives. In a second step, the project developer acts independently with full knowledge of the government's decision. This kind of solution is called the Stackelberg's solution. Fig. 1 presents the hierarchical structure of the bilevel model.

Therefore, the bilevel model is given by:

$$min_{0\le\alpha\le1}\mathbb{E}[P] = (1-\alpha)b_j + \alpha\left(c_j^* - e_j\right) \tag{12}$$

s.t.:

$$max_{b_j}\mathbb{E}\left[\pi_j\right] = \left((1-\alpha)\left(b_j - c_j^* + e\right) - 0.5\gamma e^2\right) \tag{13}$$

s.t.

$$b_j < h,\quad with\ \ h = \min\left(b_{i-\{j\}}\right)i, j = 1, \ldots, n \tag{14}$$

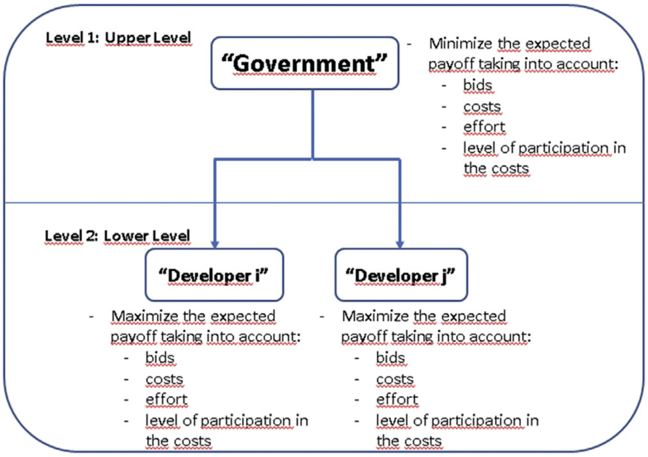

Fig. 1. Hierarchical structure of the bilevel model.

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[3] The Arrow-Pratt measure is used to calculate the investor's risk premium based on the knowledge of the variance of the benefit (Var[π_j]) and risk aversion (ρ), so the risk premium, according to Pratt-arrow, is equal to 0.5Var[π_j]ρ.

$$e_j = \frac{(1-\alpha)}{\gamma} \tag{15}$$

$$(1-\alpha)\left(b_j - c_j^* + e\right) - 0.5\gamma e^2 - 0.5\rho(a-1)^2\sigma^2 \geq 0 \tag{16}$$

The solutions to the problem of project developer j, whose equations are (13)–(18), are:

$$e_j^* = \frac{(1-\alpha)}{\gamma} \tag{17}$$

$$b_j^* = \left\{ \begin{array}{ll} 1, & \mathit{if}\ \rho > 0,\ 0 \leq \alpha \leq 1,\ c^* > 0,\ \sigma^2 > 0, \\ & 0 < \gamma < \dfrac{-1+a}{-2c - \rho\,\sigma^2 + a\rho\,\sigma^2},\ h > 0 \\ 1 + c^* - \dfrac{(1-\alpha)\left(1 - \gamma\rho\,\sigma^2\right)}{2\gamma}, & \mathit{if}\ \rho > 0,\ 0 \leq \alpha \leq 1,\ c^* > 0,\ \sigma^2 > 0, \\ & \gamma > \dfrac{(1-\alpha)}{2c + \rho\,\sigma^2(1-\alpha)},\ h > 0 \end{array} \right\} \tag{18}$$

It is observed that the optimal offer from developer j will depend on five factors: i) level of cost shared by the government (α), ii) risk aversion of the developer (ρ), iii) project costs (c_i^*), iv) positive coefficient of the cost effort (γ), and v) volatility of the unexpected costs (σ^2).

The optimal solutions for the effort and bid are constraints to take into account in the minimization problem of the expected payment proposed by the government.

Therefore, the bilevel model can be rewritten as:

$$min_{0 \leq \alpha \leq 1} \mathbb{E}[P] = (1-\alpha)b_j + \alpha\left(c_j^* - e_j\right) \tag{19}$$

s.t.:

$$e_j = \frac{(1-\alpha)}{\gamma} \tag{20}$$

$$b_j = \left\{ \begin{array}{ll} 1, & \mathit{if}\ \rho > 0,\ 0 \leq \alpha \leq 1,\ c^* > 0,\ \sigma^2 > 0, \\ & 0 < \gamma < \dfrac{-1+a}{-2c - \rho\,\sigma^2 + a\rho\,\sigma^2},\ h > 0 \\ 1 + c^* - \dfrac{(1-\alpha)\left(1 - \gamma\rho\,\sigma^2\right)}{2\gamma}, & \mathit{if}\ \rho > 0,\ 0 \leq \alpha \leq 1,\ c^* > 0,\ \sigma^2 > 0, \\ & \gamma > \dfrac{(1-\alpha)}{2c + \rho\,\sigma^2(1-\alpha)},\ h > 0 \end{array} \right\} \tag{21}$$

The solution of the bilevel model gives the optimal participation of the government in the incentive contract:

$$\alpha^* = \left\{ \begin{array}{l} \dfrac{\gamma\left(1+\rho\sigma^2\right)}{\left(1+\gamma\rho\sigma^2\right)} - \sqrt{\dfrac{(\gamma-1)^2}{\left(1+\gamma\rho\sigma^2\right)}},\ \mathit{if}\ \sigma^2 > 0, \gamma > 1,\ c^* > 0, \rho > 0 \\ \dfrac{\gamma\left(1+\rho\sigma^2\right)}{\left(1+\gamma\rho\sigma^2\right)},\ \mathit{if}\ \sigma^2 > 0, 0 < \gamma \leq 1,\ c^* > 0, \rho > 0 \end{array} \right\} \tag{22}$$

The project developer, knowing this participation level, would be encouraged to present an optimal bid:

$$b^* = \left\{ \begin{array}{ll} c^*, & \mathit{if}\ \sigma^2 > 0, \gamma > 1,\ c^* > 0, \rho > 0 \\ c^* - \dfrac{(\gamma-1)^2}{2\gamma + 2\gamma^2\rho\sigma^2}, & \mathit{if}\ \sigma^2 > 0, 0 < \gamma \leq 1,\ c^* > 0, \rho > 0 \end{array} \right\} \tag{23}$$

If it is too expensive for the developer to make the effort, the effort cost coefficient (γ) is greater than 1, thus, they will present an offer equivalent to the cost of the project (c_i^*).

If the positive coefficient of the cost effort (γ) is a value between 0 and 1, the cost decreases by a factor (DF) equivalent to: $DF = (\gamma-1)^2/2\gamma + 2\gamma^2\rho\sigma^2$.

The factor by which the cost decreases is lower if three factors increase: risk aversion, variance of the unexpected costs and coefficient of the effort costs. This implies that the offers by project developers will get increasingly close to the cost of the project. When the variance of the unexpected costs of risk-averse developers tends to infinity then, the cost effort tends to zero. Thus, in these cases, the developer finds making the effort too expensive,

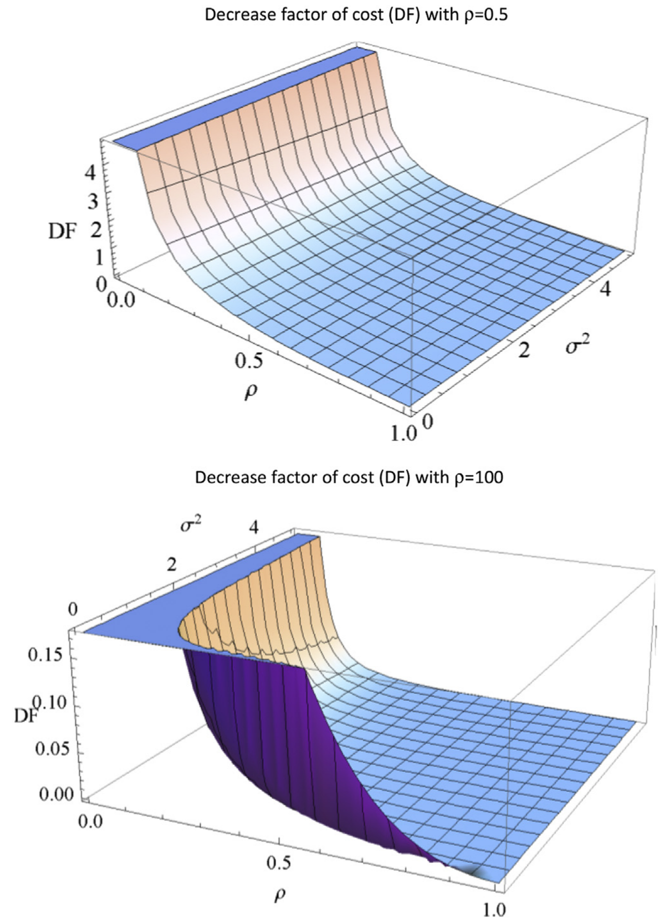

Fig. 2. Behavior of the decrease factor of cost considering risk aversion, the coefficient of effort costs and uncertainty in unforeseen costs.

because of the uncertainty of the project; therefore, their bid will be equal to the cost of the project (see Fig. 2).

With risk-averse developers, it is observed that, if the unexpected costs variance increases, then, the principal will increase their participation, exposing the winning developer to lower randomness.

If the effort cost coefficient (γ) varies between 0 and 1, i.e., for a developer it is not so expensive to make the effort, if they are risk-averse, the government's participation in the incentive contract tends to be equal to the positive effort cost coefficient (γ). If the uncertainty cost starts increasing, then, the participation of the government will tend to 1 (see Fig. 3). On the other hand, risk developers will be protected by the government to a greater extent (participation of the government will tend to 1 at a faster rate compared with risk-averse developers), without taking into account the variance of the unexpected costs (see Fig. 4).

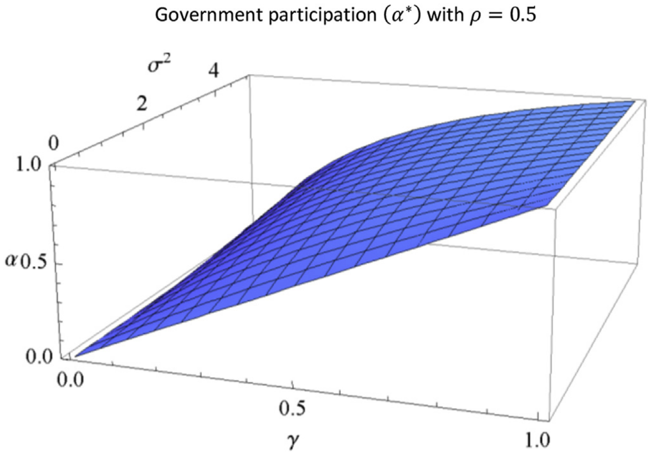

Fig. 3. Behavior of government involvement considering low coefficient of risk-aversion (ρ), low coefficient of effort costs (γ) and uncertainty in unforeseen costs (σ^2).

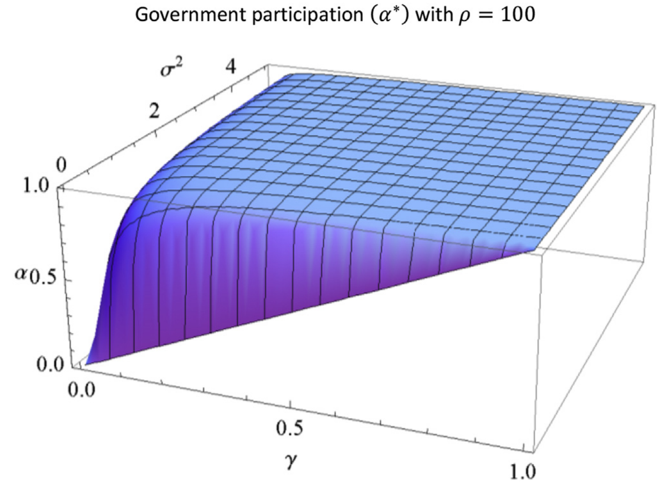

Fig. 4. Behavior of government involvement considering high coefficient of risk-aversion (ρ), low coefficient of effort costs (γ) and uncertainty in unforeseen costs (σ^2).

If the effort cost coefficient (γ) is greater than 1, then, it is expensive for developers to make the effort and the government is willing to protect risk-averse developers with lower effort cost coefficients. This participation increases if the uncertainty of the costs of these developers increases. The government will not participate if risk-averse developers present high cost efforts, even if they do not have uncertainty in the unexpected costs (see Fig. 5).

Finally, the government is not willing to participate in the cost of the project with risky developers if the variance of the unexpected costs is almost zero. However, if this variance starts to increase, the

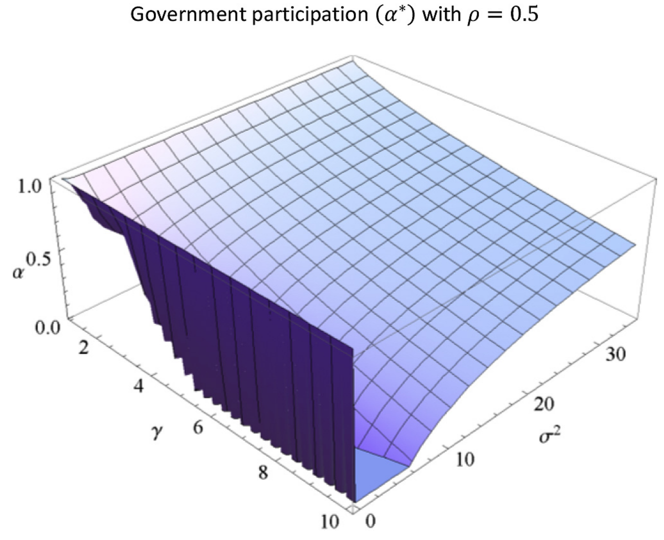

Fig. 5. Behavior of government involvement considering low coefficient of risk-aversion (ρ), high coefficient of effort costs (γ) and uncertainty in unforeseen costs (σ^2).

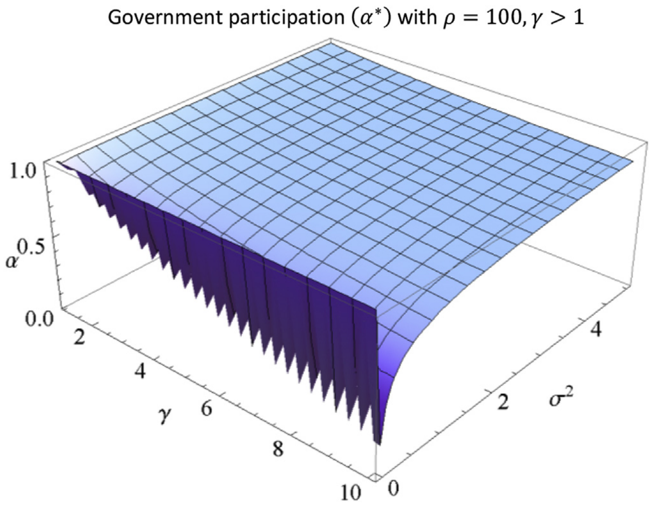

Fig. 6. Behavior of government involvement considering high coefficient of risk-aversion (ρ), high coefficient of effort costs (γ) and uncertainty in unforeseen costs (σ^2).

participation of the government increases as well, at a higher rate compared to the case of risk-averse developers (see Fig. 6).

The incentive contract model proposed allows the government to encourage the disclosure of costs of wind project developers, generating competition and sharing the risk The big advantage is that this is an easy tool to implement for the government using a deterministic auction. The software used for the solution of this linear programming problem with a unique solution, since the region to optimize is bounded, is Mathematica [43].

3. Results and discussion

3.1. Implementation of the allocation of wind investments through a reverse auction: the Colombian case

To implement the allocation of wind investment in the NIA, only zones with winds above 3.5 m/s will be used, with and without electrical service.

First, the government announces the project to be auctioned, and clarifies that the developer to be chosen will be the one with the lowest subsidy request. However, the selected firm will sign a linear incentive contract determined by the initial offer and the actual cost incurred by the project developer, whose weight will be determined by the government, taking into account some features of the project developer. In a similar vein [31], propose a model for the assessment of an expansion plan for transmission. They define a principal-agent model and a contract design in order to establish the relationship between the principal (regulator) and the agent (transmission carrier).

The project auctioned includes medium-size wind turbines in one of the coastal municipalities of Cauca and Nariño, the project size is 4600 kW. The lifetime of the wind turbine to be installed is 20 years. During that period, the auction winner will receive income for: i) payment of the contract incentive won through the auction, and ii) payment of generation fees approved by CREG corresponding to the NIA.

The government will define a reference cost for the project to be developed, which includes the value of assets and the administration, operation and maintenance costs, which is estimated as constant for all the years of the lifetime of the project (4% of total investment). An annual discount rate of 10% is assumed. The government cannot observe the true cost faced by bidders. It is also assumed that the reference value coincides with the true value.

Table 1
Features of bidders.

Developer of project	n1	n2	n3	n4	n5
Risk aversion−ρ	2	0.7	1	0.8	0.8
Effort cost coefficient − γ	0.7	1	0.8	0.5	0.3
Variance of unexpected costs − σ^2	10	8	12	2	6

The reference cost of a wind project of 4600 kW has been estimated to be $11,063M Colombian pesos, which is equivalent to an annual payment of $1,300M Colombian pesos. It is assumed that the capacity of the project is covered by seven medium sized wind turbines of 660 kW, each with three blades with a diameter of 47 m and a height of 45.7 m. With an average estimated speed of 6 m/s and a utilization factor of 28%, it is estimated that the energy produced by wind turbines each year would be 3.2 GWh. Thus, the cost of wind generation that pays for the investment and administration, operation and maintenance costs, is $416.02/kWh.

3.2. Features of bidders

Data for potential bidders to participate in the reverse auction to develop wind projects in the NIA is shown below. Because these projects have a certain degree of specialization, we are assuming that the number of non-risk-averse bidders is 5.

Given that the government is performing a first-price sealed bid auction, which encourages the entry of participants who try to bid close to their average costs [23], it is assumed that the five bidders have effort cost coefficients varying between 0 and 1.

Also, since the government is guaranteeing the subsidy to the issue of bonds in which the private sector participates (institutional investors), it is assumed that the risk aversion of the bidders is not very high, being similar among them (see Table 1).

The variance of the unexpected costs is given in $/kWh and varies between 0.5% (for bidder n4) and 3% (in the case of bidder n3).

3.2.1. Implementation of the auction allocation considering moral hazard

From the parameters that characterize bidders, the decrease factor (DF) of cost of each wind developer can be estimated as $\left(\frac{(\gamma-1)^2}{2\gamma+2\gamma^2\rho\sigma^2}\right)$, as well as the optimal bid by each bidder.

The winner of the auction is n5 because they seek the lowest subsidy: $415.69/kWh. Bidder n5 is the one with the lowest coefficient in the cost function; although they are the bidder with less risk aversion. For n5, the government will participate in the incentive contract with $\alpha^* = 0.7131$.

3.2.2. Sensitivities to changes of the successful bidder

If risk aversion of the winning bidder, n5, varies within the range of risk aversion of their competitors, keeping their other characteristics and those of their competitors constant, bidder n5 should remain the winner. If the winning bidder had a lower level of risk aversion, the bid of n5 would remain the lowest (*see* Fig. 7).

Table 2
Decrease factor and optimal bid.

Developer of project	n1	n2	n3	n4	n5
Decrease factor: $\frac{(\gamma-1)^2}{(2\gamma+2\gamma^2\rho\sigma^2)}$	0.0043	0	0.00236	0.1389	0.3347
Bid: $b^* = c^* \frac{(\gamma-1)^2}{(2\gamma+2\gamma^2\rho\sigma^2)}$	416.02	416	416.018	415.88	415.69

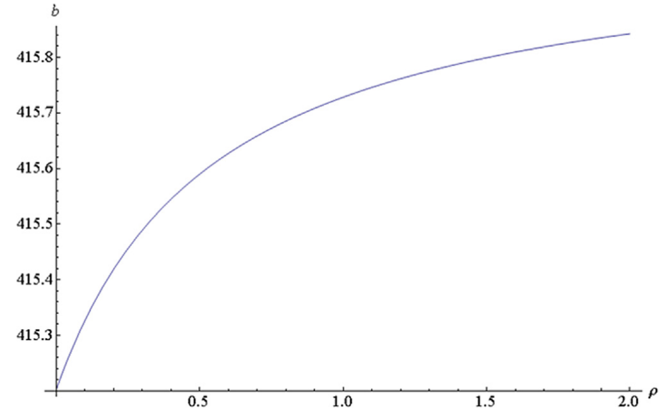

Fig. 7. Behavior of n5 bid when varying the risk aversion coefficient (ρ), with $\sigma^2 = 6$ and $\gamma = 0.3$.

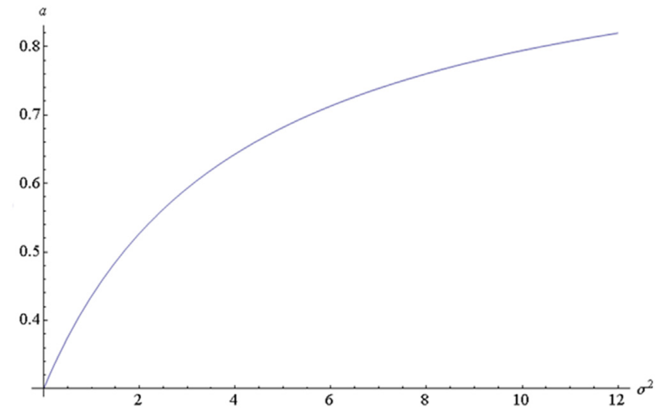

Fig. 10. Government participation in the incentive contract of n5 when varying the variance of unexpected costs (σ^2), with $\rho = 0.8$ and $\gamma = 0.3$.

Government participation increases to the extent that the developer of the winning project presents greater risk aversion, varying between 0 and 0.85, which would be the level of participation that the government would give to bidder n5, if their risk level had not been 0.8 but 2 (*see* Fig. 8).

If the winning bidder has been subjected to a variance of their unexpected costs varying between 0 and 12, keeping their other characteristics and those of their competitors constant, their bid would remain the lowest, similar to the risk aversion case.

In this case, the government participation would have increased because the unexpected costs of the winner present greater uncertainty (Figs. 9 and 10).

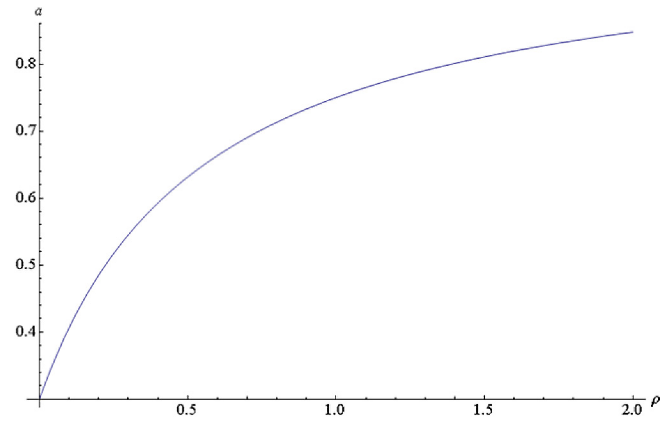

Fig. 8. Government participation in the incentive contract of n5 when varying the risk aversion coefficient (ρ), with $\sigma^2 = 6$ and $\gamma = 0.3$.

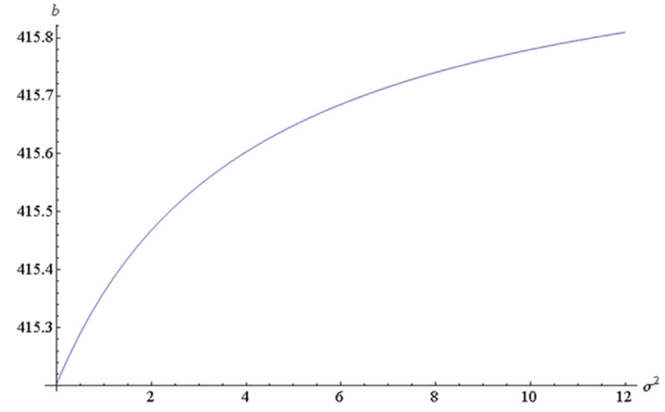

Fig. 9. Behavior of n5 bid when varying the variance of unexpected costs (σ^2), with $\rho = 0.8$ and $\gamma = 0.3$.

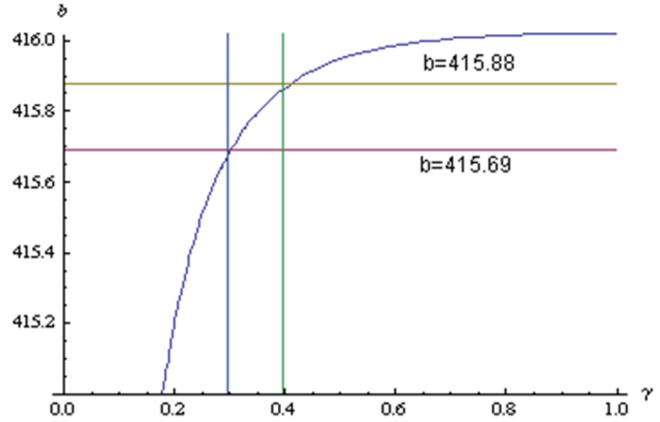

Fig. 11. Behavior of the offer of n5 when varying the coefficient of the effort cost function (γ), with $\sigma^2 = 6$ and $\gamma = 0.3$.

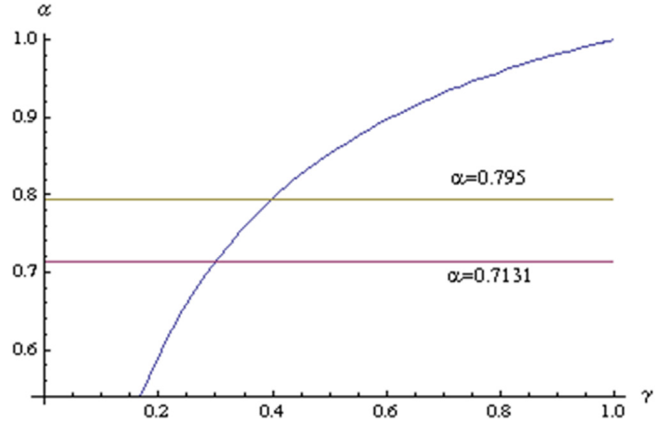

Fig. 12. Government participation in the incentive contract of n5 when varying the coefficient of the effort cost function (γ), with $\sigma^2 = 6$ and $\gamma = 0.3$.

Finally, n5 will remain the winner of the first-price auction only if the effort cost coefficient is less than 0.4, keeping their other characteristics and those of their competitors constant. The maximum contribution that the government would have in the incentive contract to be allocated to n5, with $\gamma = 0.4$, would be 0.7945. In the case that the coefficient (γ) exceeded 0.4, the winner of the auction would be n4 (see Figs. 11 and 12).

It is observed that the characteristics of the winning bidder, n5, are not the best in terms of risk aversion and uncertainty in unexpected costs. However, the government contract achieves a trade-off between these characteristics, promotes competition, lowers risk aversion of the participants to share project risks, and provides incentives for reduction in the project cost.

Also, a bilevel principal-agent model has been proposed to solve the wind project assignment problem in a rational way.

4. Conclusions and policy implications

The policy to promote renewable sources in Colombia has been part of the National Development Plan of the last two governments. However, although they had the intention of developing these sources, they have not been carried out. The ideal situation would be that policies promoting renewable energies would become state policies, since they respond to fundamental interests for the country and transcend time without being affected by changes in the government.

The proposed reform of the Colombian electricity sector contains incentives needed for renewable sources, because investment and operating costs exceed the costs of conventional technologies for which yields are uneconomical.

A comprehensive policy measure such as the one being proposed here involves four factors: i) the level of renewable penetration, ii) mechanisms for financing new investments, iii) how to allocate these resources, and iv) necessary regulatory changes. The results are focused on increasing the electricity sector coverage, which will tend to provide a better quality of life for inhabitants of remote areas that do not have electricity, and diversify the composition of the energy mix.

The main recommendations arising from this work are based on four aspects: i) definition of distributed generation (wind) as part of the electricity supply chain, and ii) definition of incentive mechanisms for the use of renewable energies that are appropriate for the characteristics of the country. The possible deployment of distributed generation in Colombia must be supported by a stable regulatory framework. This will neutralize potential threats that may impede the implementation of feasible projects through mechanisms for easy and secure connection as part of the Network Code, where rational planning approaches are used.

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