Geospatial Levelized Cost of Energy in Colombia: GeoLCOE

Alejandro Castillo-Ramírez
GIMEL—Research Group
University of Antioquia
Medellin, Colombia
Email: alejandro.castillor@udea.edu.co

Diego Mejía-Giraldo
Dept. of Electrical Engineering
University of Antioquia
Medellin, Colombia
Email: diego.mejia@udea.edu.co

Julián D. Giraldo-Ocampo
GIMEL—Research Group
University of Antioquia
Medellin, Colombia
Email: ingenieria@juliangiraldo.co

***Abstract*—This work presents a geospatial computational tool—GeoLCOE—for estimating the levelized cost of energy (LCOE) of multiple power generation technologies in Colombia. This tool is designed for assessing both economically and technically new generation projects across the Colombian geography. This tool computes the LCOE of renewable and non-renewable generation technologies for multiple locations based on geospatial data of energy resources. GeoLCOE allows to identify promising places for the construction of new generation projects. The objective of this tool is to provide the Colombian planner with additional assistance for the generation expansion planning.**

***Index Terms*—Geospatial, investment, levelized cost of energy, maintenance, operation, planning.**

I. Introduction

The worldwide continuous search for clean, sustainable, and innovative power production methods has motivated a significant number or countries to study and develop alternatives for adapting them to local situations. In particular, Colombia is currently "paving the way" to promote important penetration and use of renewable energy. Although Colombia's energy mix has been dominated by hydro power, both the regulation and planning entities have made crucial efforts for adding diversity to the energy mix. Recently, the law 1715[1] has been promoted to encourage the construction of new renewable power plants across the country. This fact suggests that a remarkable growth in renewable power can be expected in the coming years. Currently, Jepirachi has been the only wind farm built in Colombia since 2004 [1], which provides 20 MW of installed capacity. UPME, the governmental entity in charge of planning jointly the power and mining sectors in Colombia, is acting to respond to this imminent necessity of studying, exploring, and encouraging the construction of non-conventional renewable power plants in Colombia. Indeed, UPME and University of Antioquia have legally agreed in updating and constructing a computational tool for the economic evaluation of new generation projects, which is the subject of this work. This work describes a computational tool for computing the levelized cost of energy (LCOE) of different power production technologies (renewable and fossil-fuel fired power plants) at different geographical locations. The LCOE concept was developed in 1984 by the International Atomic Energy Agency for assessing economically one specific generation project [2]. Our start point is the basic concept; but our formulation considers an important number of cost components to make it more realistic. This formulation is coded in an online tool where the user can analyze, share, save, and perform sensitivity analysis against different input parameters. Although any user can access to this tool, our main purpose is to assist UPME with a geo-spatial economic and technical assessment of several power technologies like solar photovoltaic, solar thermal, small hydro, onshore wind, geothermal, biomass, coal, natural gas, among others. The tool considers a significant number of aspects related to the Colombian case like taxes, transportation costs, energy resources, among others. Since most of these aspects actually change region by region, so will the final LCOE.

[1]http://wsp.presidencia.gov.co/Normativa/Leyes/Paginas/2014.aspx

II. LCOE for the Colombian Energy Portfolio

A. General LCOE concept

The LCOE is the cost per unit of energy that considers all of the costs over the lifetime of a power plant. The LCOE is seen as the constant price over the lifetime of the project at which electricity should be sold in order to cover the investment cost, the debt and interests, rent and other type of taxes, the operation and maintenance costs, the replacement of equipment, and a return to investors [3]. Following the methodology illustrated in [3], we have arrived to the following expression for LCOE:

$$LCOE = LCOE_I + LCOE_v + LCOE_f + LCOE_g \quad (1)$$

Each of the terms described in equation (1) represent the cost components due to investment $LCOE_I$, variable operation and maintenance $LCOE_v$, fixed operation and maintenance $LCOE_f$, and fuel $LCOE_g$.

B. LCOE components

- *Overnight costs*. In particular for every technology, we have adopted EIA's structure (described in [4]) for splitting the investment costs as: civil engineering, mechanical equipment, electrical equipment, indirect costs, owner costs. Each of these cost components has been adapted to the Colombian situation. For instance, in civil engineering, we have considered different access road types according to its length; in the case of mechanical and electrical equipment, import costs and taxes have been considered so as to obtain although higher, more realistic LCOE values. Also, local transportation costs have been included in this formulation. All of these features represent geospatial data that is coded within GeoLCOE. Mathematically, the investment cost component $LCOE_I$ is computed as:

$$LCOE_I = \Delta \frac{I}{\sum_{t=1}^{T} E_t \gamma^t} = \Delta \frac{I}{8760\, CF \, \sum_{t=1}^{T} y_t \gamma^t} \quad (2)$$

where I is the total overnight cost in USD/MW, CF the capacity factor.

The tax factor Δ comprises the effect of the rent tax α, depreciation d_t, depreciation period T_0, the discount rate γ, and investment tax credit i, and lifetime T of the project. It is obtained as follows:

$$\Delta = \frac{1-i}{1-\alpha} \left[1 - \alpha \sum_{t=1}^{T_0} d_t \gamma^t - (1-\alpha) \left(1 - \sum_{t=1}^{T_0} d_t \gamma^t \right) \gamma^T \right] \quad (3)$$

- *Operational costs*. For every technology, we have constructed a structure for operational and maintenance costs (O&M): fixed operation and maintenance; variable operation and maintenance, environmental management, insurance, law charges, replacement, salvage value, and decommissioning. In the case of fixed O&M costs, we have also considered salaries and the maintenance of different elements like plant, lines and substation, access roads, pipes, and connections. Mathematically,

$$LCOE_v = \frac{\sum_{t=1}^{T} v_t \, E_t \gamma^t}{\sum_{t=1}^{T} E_t \gamma^t} = \frac{\sum_{t=1}^{T} v_t \, y_t \gamma^t}{\sum_{t=1}^{T} y_t \gamma^t}. \quad (4)$$

$$LCOE_f = \frac{\sum_{t=1}^{T} f_t \gamma^t}{\sum_{t=1}^{T} E_t \gamma^t} = \frac{\sum_{t=1}^{T} f_t \gamma^t}{8760\, CF \, \sum_{t=1}^{T} y_t \gamma^t}. \quad (5)$$

where v_t and f_t represent the total variable and fixed O&M costs respectively, E_t is the yearly energy production, and y_t the degradation factor of the technology.
- *Fuels*. Coal, natural gas, and fuel oil power plants were also considered in GeoLCOE given the significant participation in the Colombian energy mix [5]. Departments like Guajira, Córdoba, and Cesar provide most of the coal reserves in Colombia, which are approximately 5,300 billion tons of coal. In terms of natural gas, the 2012 Colombia's reserves-to-production ratio was 16.6 years according to the 2014 ANH report [6], which indicates simple-cycle and combined-cycle units will continue participating in the market. Fuel prices were regionalized according to production price and transportation costs. Seven, two, and two production locations were used for coal, natural gas, and fuel oil respectively. Different types of roads and trucks were considered for coal and fuel oil transportation costs. In the natural gas case, a regionalization scheme proposed by the regulator[2] was used for transportation cost computation. Mathematically,

$$LCOE_g = H \frac{\sum_{t=1}^{T} g_t \, E_t \gamma^t}{\sum_{t=1}^{T} E_t \gamma^t} = H \frac{\sum_{t=1}^{T} g_t \, y_t \gamma^t}{\sum_{t=1}^{T} y_t \gamma^t}. \quad (6)$$

where g_t represents the fuel price (in USD/MBTU), and H the heat rate (in MBTU/MWh).
- *Externalities*. The current version of GeoLCOE evaluates the environmental impacts on greenhouse gas emissions caused by fossil fuel-fired power plants operation. The model estimates the CO_2 and NO_x emissions as the product between the emissions factor of the plant and its potential production. The LCOE impact is then computed by assigning a tax rate that the plant owner would have to pay per each metric ton of either CO_2, NO_x, or SO_2. The analytical impact of externalities in the final LCOE is as follows:

$$LCOE_{ext} = H \frac{\sum_{t=1}^{T} \rho_t \, E_t \gamma^t}{\sum_{t=1}^{T} E_t \gamma^t} = H \frac{\sum_{t=1}^{T} \rho_t \, y_t \gamma^t}{\sum_{t=1}^{T} y_t \gamma^t} \quad (7)$$

where the term $\rho_t = G^{\mathrm{CO_2}} \rho_t^{\mathrm{CO_2}} + G^{\mathrm{SO_2}} \rho_t^{\mathrm{SO_2}} + G^{\mathrm{NO}_x} \rho_t^{\mathrm{NO}_x}$ is the equivalent tax rate of per unit of electricity of year t (in USD/MWh). $G^{\mathrm{CO_2}}, G^{\mathrm{SO_2}}$, and G^{NO_x} represent the metric tons per MBTU of CO_2, SO_2, and NO_x that are thrown to the atmosphere respectively. Each of the $\rho_t^{\mathrm{CO_2}}, \rho_t^{\mathrm{SO_2}}$, and $\rho_t^{\mathrm{NO}_x}$ is the emission tax rate (in USD/MeTon) imposed to CO_2, SO_2, and NO_x respectively.

III. Geo-Spatial LCOE

GeoLCOE is an online tool able to compute the LCEO for multiple generation technologies as well as for multiple geographic locations in Colombia using cost-related information. The tool is created for assisting the planner in the decision-making process of deciding where and which type of power plant to install. This tool has been developed following the idea of social knowledge; the user of GeoLCOE can create, modify, store, and share different analysis with his/her colleagues.

A. Software Architecture

The overall software architecture is based on both a Back-End and and Front-End as illustrated in Fig. 1. The Back-end is composed of an ArcGIS map server and an Oracle database. The scheme of installation of ArcGIS does not affect the operation of the system (GeoLCOE), and the alphanumeric data structures are accessible through connections made in .NET. The system is also based on a Front-End, which is mostly developed in Javascript frameworks and technologies

[2] Resolución Comisión Regulación de Energía y Gas (CREG) 126 de 2010

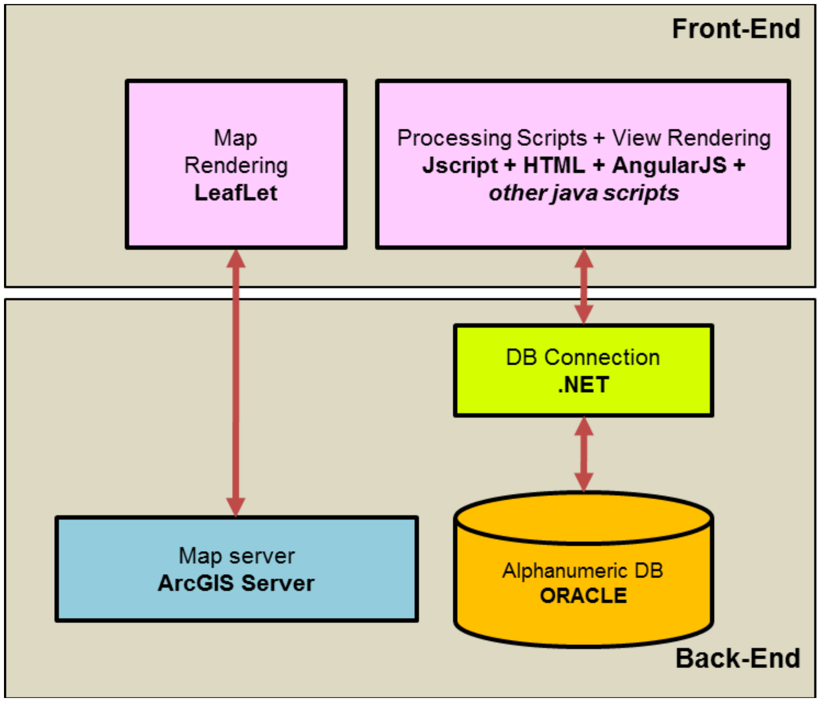

Fig. 1. General software architecture

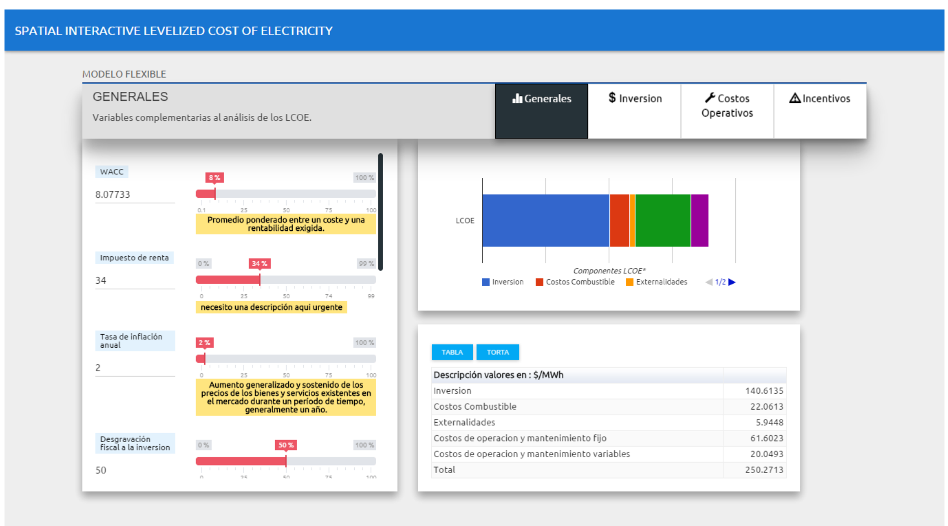

Fig. 2. Flexible project screenshot

such as HTML AngularJS for views and leaflet for rendering maps.

B. Tool modules

In order to give an idea of what this tool does, this section provides the two main modules in which the software is divided. The modules are classified according to the detail level of the cost structure and geographic modeling:

- *Flexible Projects*: this interface represents a LCOE calculator at a low level of cost detail. It provides the LCOE of a single geographical point. It can compute the LCOE for any generation technology by entering the data accordingly. Input data can be modified easily so as to perform sensitivity analysis. LCOE results are displayed in real-time numerically and through bar plots. Fig. 2 is a screenshot of the user interface for creating flexible projects.
- *Parameterized Projects*: this interface represents the complete LCOE calculator at a high level of cost detail. Each generation technology will ask the user for a different set of data. Energy resources coded as maps are necessary for these modules to work. There is a geographic viewer for

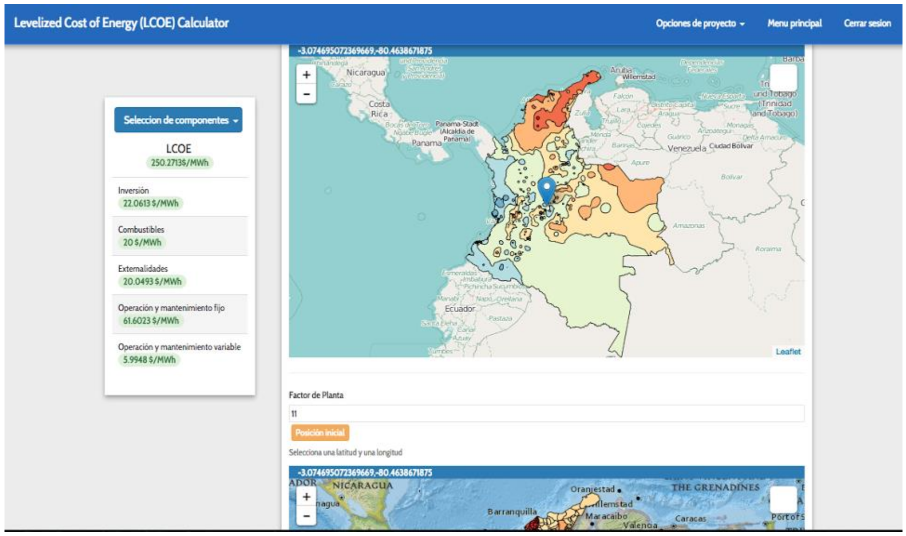

Fig. 3. Parameterized project screenshot

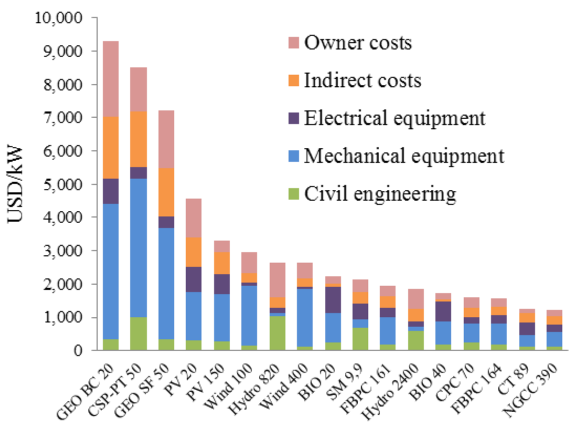

Fig. 4. Overnight costs of different technologies

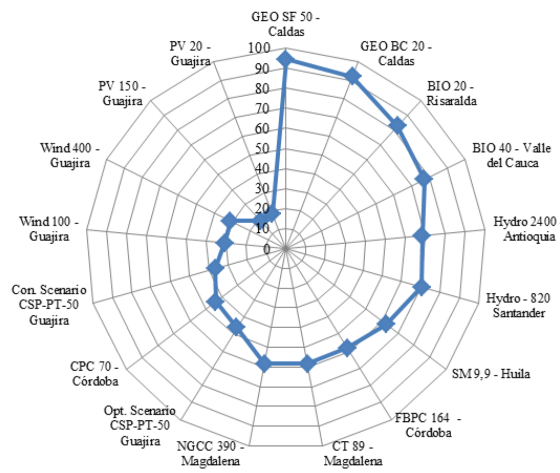

Fig. 5. Capacity factor of different technologies

each geospatial variable for proper result analysis. The user can choose the geographic location to perform the LCOE analysis. Fig. 3 is a screenshot of the user interface for creating parameterized projects.

IV. LCOE RESULTS

In this section we present LCOE results related to a specific location. 17 different power plant of different sizes and technology were assessed: Concentrated Solar Power Parabolic Trough (CSP-PT); Geothermal Binary Cycle (Geo BC); Solar Photovoltaic (PV); Wind (Wind), Natural Gas Combined Cycle (NGCC), Conventional Turbine (CT), Conventional Pulverized Coal (CPC), Geothermal Single Flash (Geo SF), Fluidized Bed Pulverized Coal (FBPC), Biomass (Bio), Hydro-large (Hydro) and Small Hydro (SM).

Results consider incentives and taxes according to the technology under study. Renewable generation technologies consider economic incentives as stated in Law 1715 of 2014; whereas conventional power plant models consider different types of taxes (value-added tax, tariff, and environmental development tax[3]). It is important to clarify that these results do not necessarily represent the real overnight costs and LCOE of a particular operating power plant; however, they are the product of a rigorous and detailed cost item specification and estimation for each generation technology.

Fig. 4 shows the overnight costs computed for each of the projects labeled underneath the horizontal axes. These are constructed based on both system design and project location. In this study, Geo BC is the technology with the highest cost per kW of installed capacity. This represents an estimation of a geothermal project located in the Ruíz volcano area. On the other hand, NGCC power plants presents the lowest investment cost. Wind power overnight costs are approximately twice the NGCC's.

[3]Known as "transfers tax" in Colombia

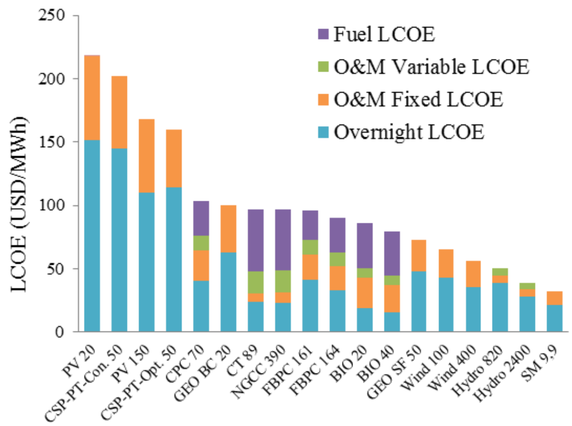

Fig. 6. LCOE components

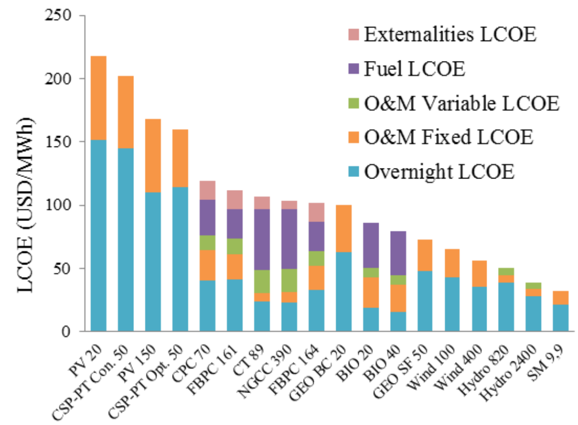

Fig. 7. LCOE components

Fig. 5 shows the capacity factor CF used for LCOE computation. Renewables like PV and Wind present a relatively low CF. The CF of wind and solar is computed based on wind speed and solar radiation maps respectively [7], [8]. These contain monthly average values which allow us estimate the annual energy production of these two technologies. In the case of dispatchable technologies (like coal and natural gas), CF was estimated based on theoretical and practical assumptions.

Fig. 6 shows the LCOE for each of the projects labeled underneath the horizontal axes. Apart from the project location, LCOE also considers resource availability as mentioned previously. LCOE results indicate that hydroelectric power plants are those that have the lowest LCOE, while solar PV is still high; however, as long as installed capacity increases, the effect of economies of scale causes its LCOE to decrease (see PV 20 vs PV 150.) On the other hand, wind power is becoming a more attractive renewable technology, its LCOE is comparable with NGCC, CT, and coal. It is necessary to recall that these results are proper of a particular location; therefore, geographical distribution of LCOE can significantly change across the country.

According to the results illustrated in Fig. 6, it is still evident that hydro power plants are the most economical in Colombia. In particular, small run-off river plants present the lowest LCOE compared to large hydro power plants (with reservoir). This result is explained by the regulatory incentives designed for non-conventional energy production technologies like small run-off river plants. Apart from hydro power technologies, wind, geothermal, and biomass are other set of technologies whose LCOE is relatively low.

Although it is said[4] that the gross hydropower energy potential in Colombia is approximately 93 GW, only 33 GW is the final potential left for new projects. Although this potential is still considerable, it has decreased notably. Thus, it is extremely important achieving a diverse energy production market mainly focused on non-conventional renewable energy, which is part of the solution for attending the steady electricity demand growth in a sustainable fashion.

[4]Unidad de Planeación Minero-Energética—UPME: www.upme.gov.co

Finally, we have also included in the GeoLCOE theoretical models of solar thermal and solar photovoltaic technologies. Based on our LCOE results, these two technologies are still expensive to be considered in the Colombian generation system. The high overnight cost of these technologies is what makes their LCOE reasonably high.

On the other hand, the LCOE of traditional thermal power plants like coal and natural gas resulted in similar levels. However, it is worth to mention that these values are very sensitive to the conditions of each particular project and market behavior. The latter significantly influences the capacity factor described in our model since this captures the yearly energy production. The case of dispatchable resources is somewhat especial. These technologies can control their output in a physical manner. So, in a market environment, the annual production levels of thermal power plants is uncertain. The market strategic behavior of generating companies can significantly influence the amount of electricity they provide to the network. Therefore, establishing an average capacity factor throughout the lifetime of the project is not straightforward. Our capacity factors are based on historical records of major thermal power plants located in Colombia [9].

According to [10], Colombia is especially a vulnerable country to weather change given that part of its population is located close to flood and unstable (hilly) areas. Apart from the risk, there are also multiple historical records that indicate the high frequency of occurrence of natural disaster events. These facts especially motivated the modeling of environment-related externalities like greenhouse gas emissions as exposed in section II. The LCOE results consider the economic impact of emissions caused by coal and natural gas power plants. In this study, we imposed a tax rate of \$16 USD per Metric Ton of greenhouse gas emitted. As illustrated in Fig. 7, these considerations obviously increase the LCOE of fossil-fueled power plants. However, there are other multiple externalities related to health problems and biodiversity damage that were not counted for. Research on the cost quantification of multiple externalities should be considered for a better and more comprehensive cost comparison among different power/energy production technologies.

V. Conclusions

GeoLCOE was presented and is a geospatial LCOE calculator for Colombia's power system. It is constructed for providing assistance in the decision-making process performed by UPME. GeoLCOE is loaded with Colombian data; however, the computations can be performed for *any* geographical context (or country) by properly entering data. GeoLCOE assesses economically multiple types of generation projects and allows to perform sensitivity over key parameters like the discount rate, investment tax credit, capacity factors, fuel prices, and many others. Currently, energy production models of solar (thermal and photovoltaic), wind, geothermal, and small hydro power are implemented within GeoLCOE. However, future research must be performed in order to refine primary energy resource data and models.

Acknowledgment

The authors want to thank all the researchers involved in the project "Costos Nivelados de Generación de Electricidad en Colombia", which is funded by UPME and Colciencias under contract number 0589-2013. The authors also thank to "Estrategia de Sostenibilidad 2015–2016 de la Universidad de Antioquia" for their support.

References

[1] A. Pinilla, L. Rodriguez, and R. Trujillo, "Performance Evaluation of Jepirachi Wind Park," *Renewable Energy*, vol. 34, no. 1, pp. 48–52, 2009. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0960148108001481.

[2] International Atomic Energy Agency, "Expansion Planning for Electrical Generating Systems—A Guidebook," IAEA, Tech. Rep., 1984, Vienna.

[3] S. Reichelstein and M. Yorston, "The prospects for cost competitive solar pv power," *Energy Policy*, vol. 55, no. 0, pp. 117–127, 2013.

[4] U.S. Energy Information Administration, "Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants," EIA, Tech. Rep., April 2013. [Online]. Available: http://www.eia.gov/forecasts/capitalcost/pdf/updated_capcost.pdf

[5] Unidad de Planeación Minero Energética, "Plan de Expansión de Referencia Generación-Transmisión 2014–2028," UPME, Tech. Rep., 2014. [Online]. Available: http://www.upme.gov.co/Docs/Plan_Expansion/2015/Plan_GT_2014-2028.pdf

[6] Agencia Nacional de Hidrocarburos, "Informe de Gestión 2013," ANH, Tech. Rep., Enero 2014. [Online]. Available: http://www.anh.gov.co/en-us/la-anh/Informes%20de%20Gestin/Informe%20de%20Gesti%C3%B3n%202013.pdf

[7] Unidad de Planeación Minero Energética, "Atlas de Viento y Energía Eólica de Colombia," UPME, Tech. Rep., 2006. [Online]. Available: http://www.si3ea.gov.co/Home/Energ%C3%ADaEolica/tabid/75/language/en-US/Default.aspx

[8] ——, "Atlas de Radiación Solar de Colombia," UPME, Tech. Rep., 2005. [Online]. Available: http://www.si3ea.gov.co/Home/EnergiaSolar/tabid/74/language/en-US/Default.aspx

[9] XM—Compañía de Expertos en Mercados, "Histórico de Ofertas," XM, Tech. Rep., 2013. [Online]. Available: http://informacioninteligente10.xm.com.co/oferta/Paginas/HistoricoOferta.aspx?RootFolder=%2Foferta%2FHistorico%20Oferta%2FGeneraci%C3%B3n&FolderCTID=0x01200075F2CCF9F779EE4B93D2D54764CDB78A&View={9F21C71E-AD8F-4E3F-B2EA-0B38F49A9BA8}

[10] Programa de las Naciones Unidas para el Desarrollo en Colombia, "El cambio climático en Colombia," PNUD, Tech. Rep., 2010. [Online]. Available: http://www.pnud.org.co/img_upload/61626461626434343535373737353535/Brochure%20resumen%20Proyecto.pdf