Evaluation of offshore wind energy diffusion in long-term scenarios in the Colombian Caribbean

Mateo Valencia[1], Santiago Arango[2], and Andrés F. Osorio[3]

1. Decision Sciences Group, Facultad de Minas, Universidad Nacional de Colombia, Medellín, Colombia
2. Decision Sciences Group, Facultad de Minas, Universidad Nacional de Colombia, Medellín, Colombia
3. OCEANICOS Research Group, Universidad Nacional de Colombia, Medellín, Colombia

Keywords— Diffusion model, offshore wind energy, energy policies.

I. INTRODUCTION

Since 2014 Colombia has embarked on the career of the energy transition, implementing laws that reduce or exempt Renewable Energies (RE) from taxes. Understanding the possible penetration of offshore wind energy (OWE) in the long term is essential to identify the development of this technology and its possible role in the complementarity of the country's energy matrix. The main objective of this study was to evaluate the diffusion that this energy generation technology would have through the implementation of policies or direct and indirect incentives that are adequate for the Colombian market conditions. The results of the proposed model may be helpful for long-term investment decision-making in RE.

Colombia have launched a roadmap for the deployment of OWE in the Caribbean region, this being a technology that has not yet been implemented in the country and with great potential, having initially dimensioned in this preliminary study a potential of 50 GW [1]. This planning adds to the efforts initiated by Colombia since 2014 to have carbon neutrality by 2050 [2], in order to achieve a true energy transition.

Energy matrix is composed by 67% hydroelectric plants and 27% thermal plants, which implies a high vulnerability in times of low hydrological contributions. The diffusion of offshore wind generation could meet the demand for energy when hydroelectric plants are affected by El Niño conditions (positive ENSO anomalies), making this technology the necessary counterpart to reach complementarity in dry seasons [3]. Additionally, mitigating overexposure to few types of generation sources leads to more stable and affordable prices [4].

Due to the little intermittency in the wind resource evidenced in La Guajira, it is expected to have plant factors or use of offshore wind technology close to 70% (MinEnergía, 2022), which would be very attractive for investment, since that these generation plants would have one of the highest utilization percentages in the world, which are on average between 40% and 50% [5].

Offshore wind generation shows a growth in maturity greater than other technologies at present, since technological and logistical barriers are being broken to be able to be implemented, but even so its participation in the energy generation matrix in the world barely exceeds 0.3% [5].

The achievement of a true energy transition implies a considerable change in the distribution of the energy matrix and not a simple addition of an additional source of generation, penetration that requires the implementation of policies and incentives that make investment in renewable energies more profitable, examples of these are tax reductions, Feed-in Tarif (FIT), subsidies and emission reduction certificates [6]. Therefore, it is necessary to quantify the possible amounts of income from offshore wind technology and its effects on the system.

II. METHODS

A. *Focus on System Dynamics*

In order to understand and evaluate the correct causal relationships that allow the entry of simulated technology, system dynamics is presented as a widely used tool in recent years for diffusion models [7]. Additionally, taking into account that wind energy is a technology strongly dependent on government actions [8], system dynamics is chosen in the present study to analyze incentive-based policy scenarios.

B. *OWE Infrastructure*

The areas initially contemplated by the UPME show a distinction between farms with fixed (FX) and floating foundations (FL), therefore it has been simulated based on the costs of these two different construction methodologies. The data used has been estimated based on information from entities such as NREL and IRENA [9], data from Matinez and Iglesias [10], and contrasted with the values of the Colombian context displayed in the Minenergia Roadmap.

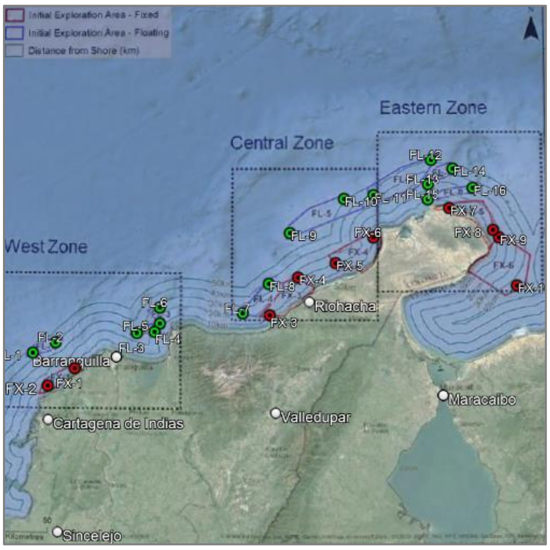

Fig. 1. Points evaluated on UPME assignment areas.

C. *Intervention sites*

Based on the areas preliminarily defined by UPME for the location assignment of offshore generation plants [1], which are shown in the Fig 1, 26 points have been evaluated within these zones, where 10 of these correspond to plants with fixed foundations and 16 to floating plants. The wind speed values of these points have been taken from the Global Wind Atlas 3.0, a portal developed by the Technical University of Denmark (DTU). With this information, a correlation was made to determine the utilization factors according to the periods of the year.

D. *Learning Curves*

Our diffusion model includes learning curves as a fundamental part of the entry behavior of a new technology, with which the investment costs in a technology decrease as the installed capacity increases. Authors such as Chi estimate learning curves for wind energy [11], where it can be seen that one of the most widely used methodologies is the two-factor or double-factor method presented in multiple investigations such as Song and Jamasb (2007)[12][13].

E. *Simulation model*

Multiple applications of diffusion models have been seen in recent years, most of them focused on wind and solar ER in developed countries and dependent on fossil sources. Zuluaga & Dyner evaluate the use of incentives for ERs in Latin America [14], and Arias-Gaviria et al. analyze incentive-based scenarios for different types of RE in Colombia [7].

Being the purpose of this study to find the effects of the entry of offshore wind technology in Colombia, the construction of a model that can represent the causal relationships when implementing policies based on incentives to promote the entry of renewable energies in the country is proposed. A model based on system dynamics is exhibited in the following sections, which is oriented as described by Sterman for this type of modelling [15].

The proposed diffusion model is based mainly on the Available potential and New installed capacity variables, which are part of the B1 balance cycle that describes the propagation behavior of an innovation according to a logistic function [14]. This S-curve shaped function describes the slow growth that is exhibited before having a certain degree of learning in a technology, subsequently shows an exponential growth in the adoption of the innovation, and finally it returns to a slow growth due to the reduction in the available potential of the system. The causal diagram shown in Fig. 2 represents the dynamic hypothesis proposed for the conceptual structure of the model, which is based on the hypothesis proposed by Arias-Gaviria et al. [7].

The B1 balance cycle of the causal diagram also represents the different stages through which the OWE in Colombia must pass, starting with the allocation of areas until the start-up. In the competitive scheme of Colombia, the government is only responsible for the process up to the level of Assigned potential, this process being carried out according to Minenergía resolution 40284 of 2022. Once the area and its associated capacity have been assigned, there is a period between 8 and 10 years for its commissioning, where each project goes through the levels of Potential in studies and licensing and Capacity under construction.

The Energy Generation represented in Eq. 5 depends on the utilization factor, which has been estimated based on the wind speed information described in Fig. 3 for the FX and FL plants. The learning rate (LR) used in Eq.7 was the value indicated by IEA for OWE [16].

Available potencial (MW)

$$P_i \qquad \frac{dP_i}{dt} = -C_{new,i} \tag{1}$$

This level is decreased with increased the New installed capacity.

New installed capacity (MW/year)

$$C_{new,i} = \alpha_i + r_i P_i \left(\frac{C_i}{P_i + C_i}\right) \tag{2}$$

Investment rate in new capacity.

Profitability

$$r_i = \frac{I_i}{E_i} \tag{3}$$

The profitability is the ratio between the total Incomes (I) and the Total costs (E).

Installed capacity (MW)

$$C_i \qquad \frac{dC_i}{dt} = C_{new,i} \tag{4}$$

The Installed capacity increases with the New installed capacity. The decrease in installed capacity was not considered because in the simulation time horizon (28 years) there will be no dismantling of the plants.

Energy Generation

$$G_i = f_i C_i \tag{5}$$

The energy generation is estimated with the Installed capacity times the utilization factor.

Levelized cost of energy (USD/MWh)

$$LCOE_i = \frac{\sum E_i}{\sum G_i} \tag{6}$$

The LCOE is the relationship between the total costs and the energy generated in the same simulated period [10].

Elasticity of learning

$$\lambda_i = \frac{\ln(1 - LR_i)}{\ln(2)} \tag{7}$$

Expression obtained from the definition of learning rate [15], based on the model of Arias-Gaviria et al. [7].

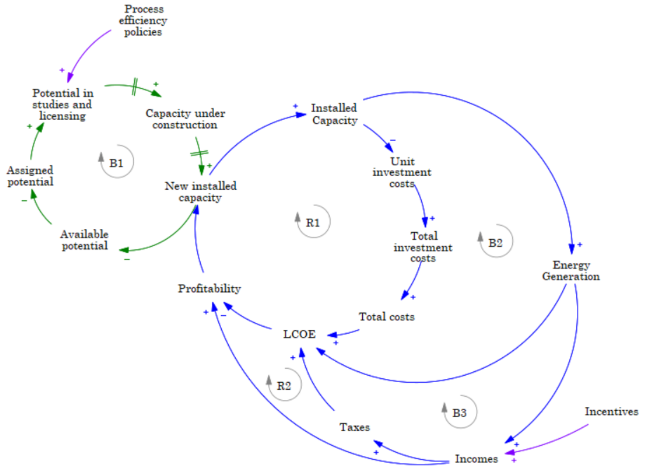

Fig. 2. Causal loop diagram for the base diffusion model.

F. *Modeling the incentive*

Some of the most used incentives to generate a favorable environment for the entry of RE in the market are feed-in tariffs (FITs), feed-in premiums (FIPs) and green tradable certificates (TGC), which encourage the deployment of these technologies [17]. Many incentives have been used throughout the world, such as those described by Reinhard, which have been implemented in the European Union [18].

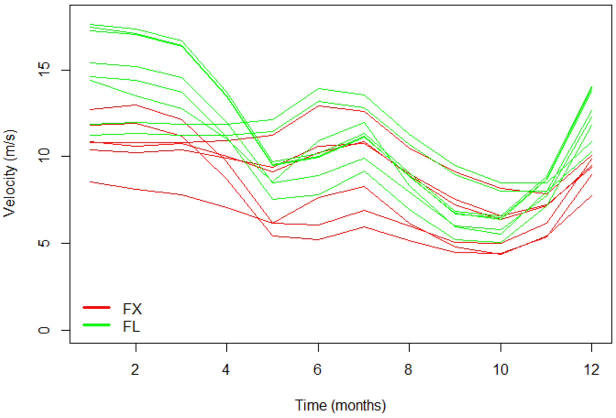

Fig. 3. Monthly mean of wind speed at 100m in the study areas.

G. *Model validation*

Since our model is a causal-descriptive tool, it is necessary to perform validations of both structure and behavior [19]. For the structure validations, the conceptualization of the model was made based on causal diagrams of some of the authors reviewed in the state of the art, applying in this step the methods of semantic analysis and formal inspections.

On the other hand, the behavioral validation that was made was to verify that the capacity income curve had an S shape, a graphic/visual method that is useful when the trend of the diffusion model is known [20].

III. RESULTS

For the simulation of the baseline scenario, we use a maximum available capacity of 19 GW, a value that is budgeted by the government for its RE goal, being a realistic limit for the time horizon of this study, which is 38% of the potential. preliminarily estimated for Colombia. Delays were applied for both construction methodologies, for the FX plants 4 years were used, since in 2023 the government assigned 10 projects in shallow areas, and for the FL 5 years because it is estimated that the allocation and construction of new OWE projects would be in the range of 5 to 7 years.

The summary of the simulated scenarios is presented in Table 1, in which the profitability and installed capacity can be seen for both the FX and FL plant types. The total added contributions of both types of plants do not vary significantly from one scenario to another, this is due to the fact that the FL plant is having a higher growth than the FX once it enters and reaches installed capacity values similar to those of the FX. Profitability in the TR scenario increases because the tax reduction is approximately 50%, a value that is highly sensitive to results and increases installed capacity. In general, all the scenarios show an increase in profitability and installed capacity, but this increase compared to the base scenario in some cases is less than 10% despite the incentives implemented, making it necessary to implement additional measures if a greater income of this technology in the country.

TABLE I
RESULTS OF SIMULATED SCENARIOS

	BS	FIT	TR	TGC
FX				
Installed Capacity (MW)	5670	6294	6124	6180
Profitability	1.18	1.24	1.42	1.22
FL				
Installed Capacity (MW)	5544	6098	5932	5988
Profitability	1.19	1.26	1.44	1.24
Total Installed Capacity (MW)	11214	12392	12056	12168
Coverage in RE target (%)	59%	65%	63%	64%

IV. DISCUSSION & CONCLUSION

According to the results of the simulation, it is evident that the entry of this technology during the first years will be slow, which enters into consensus with the capacity allocation notified by the UPME in February 2023, where the wind offshore registered 10 projects totaling 349.8 MW.

The foregoing provides an encouraging outlook for investment decisions, since an income of this technology begins to be seen in the year immediately following the Ministry's publication on offshore wind power.

The OWE is a technology that requires large capital investments, it is for this reason that reducing costs is essential for it to be competitive and penetrate the market. Costs are reduced as a considerable amount of installed capacity begins to enter, which is the effect of the learning obtained. The exponential growth is evident in the medium term, where the government expects that the first plants of more than 200 MW have been built, in the interval of the next 8 to 10 years.

Although direct incentives do not have a great incidence on the amount of installed capacity, offshore wind energy manages to exceed 10 MW in long-term scenarios, this being a high percentage of the total proposed in the national strategic plan of 19 MW in RE.

For the next updates of this work, it is intended to collect more information on CAPEX and OPEX costs in Colombia, because the information used consists of the literature review carried out for countries that have had the experience of implementing the OWE. In this way, it is expected to obtain more precise results based on the context of the country's market.

REFERENCES

[1] Minenergía, World Bank Group, "Hoja de ruta para el despliegue de la energía eólica costa afuera en Colombia," 2022. [Online]. Available: www.minenergia.gov.co/documents

[2] Ministerio de Minas y Energía de Colombia, "Transición energética: un legado para el presente y el futuro de Colombia," [Online]. Available: https://www.minenergia.gov.co/documents/5856/TRANSICION_ENERGETICA_COLOMBIA_BID-MINENERGIA-2403.pdf

[3] J. G. Rueda-Bayona, A. Guzmán, J. J. C. Eras, R. Silva-Casarín, E. Bastidas-Arteaga, and J. Horrillo-Caraballo, "Renewables energies in Colombia and the opportunity for the offshore wind technology," Journal of Cleaner Production, vol. 220, 2019. DOI: 10.1016/j.jclepro.2019.02.174

[4] Y. Wei, Q. P. Zou, and X. Lin, "Evolution of price policy for offshore wind energy in China: Trilemma of capacity, price and subsidy," Renewable and Sustainable Energy Reviews, vol. 136, 2021. DOI: 10.1016/j.rser.2020.110366

[5] International Energy Agency (IEA), "Offshore Wind Outlook 2019: World Energy Outlook Special Report," International Energy Association, 2019.

[6] T. Ackermann, G. Andersson, and L. Söder, "Overview of government and market driven programs for the promotion of renewable power generation," Renewable Energy, vol. 22, no. 1-3, 2001. DOI: 10.1016/S0960-1481(00)00015-X.

[7] J. Arias-Gaviria, S. X. Carvajal-Quintero, and S. Arango-Aramburo, "Understanding dynamics and policy for renewable energy diffusion in Colombia," Renewable Energy, vol. 139, 2019. DOI: 10.1016/j.renene.2019.02.138.

[8] X. Xu, D. Niu, B. Xiao, X. Guo, L. Zhang, and K. Wang, "Policy analysis for grid parity of wind power generation in China," Energy Policy, vol. 138, 2020, Article ID 111225. DOI: 10.1016/j.enpol.2019.111225

[9] International Renewable Energy Agency (IRENA), "Renewable power generation costs in 2017," IEA Publications, Paris, France, 2000.

[10] A. Martinez and G. Iglesias, "Mapping of the levelised cost of energy for floating offshore wind in the European Atlantic," Renewable and Sustainable Energy Reviews, vol. 154, 2022, Article ID 111889. DOI: 10.1016/j.rser.2021.111889

[11] C. J. Chi and Y. F. Ma, "Estimating the learning rate of wind power industry based on the modified learning curve theory," Research on Economics and Management, 2018, pp. 69-77.

[12] D. Song and Y. X. He, "Study on cost of wind power generation base on double-factors learning curve," Northeast Electric Power Technology, 2017, pp. 1-3.

[13] T. Jamasb, "Technical change theory and learning curves: patterns of progress in electricity generation technologies," Energy, vol. 51, 2007, pp. 51-72. DOI: 10.5547/ISSN0195-6574-EJ-Vol28-No3-4.

[14] M. M. Zuluaga and I. Dyner, "Incentives for renewable energy in reformed Latin-American electricity markets: the Colombian case," Journal of Cleaner Production, vol. 15, no. 2, 2007. DOI: 10.1016/j.jclepro.2005.12.014

[15] J. Sterman, Business Dynamics: Systems Thinking and Modeling for a Complex World, The McGraw-Hill Companies, Inc., 2000.

[16] International Energy Agency (IEA), "Experience Curves for Energy Technology," 2000.

[17] M. Baudry and C. Bonnet, "Demand-pull instruments and the development of wind power in Europe: a counterfactual analysis," Environ Resour Econ, vol. 73, no. 2, 2018, pp. 385-429.

[18] R. Haas, C. Panzer, G. Resch, M. Ragwitz, G. Reece, and A. Held, "A historical review of promotion strategies for electricity from renewable energy sources in EU countries," Renewable and Sustainable Energy Reviews, vol. 15, no. 2, 2011, pp. 1003-1034. DOI: 10.1016/j.rser.2010.11.015

[19] Y. Barlas, "Formal aspects of model validity and validation in system dynamics," Syst. Dynam. Rev., vol. 12, no. 3, 1996. DOI: 10.1002/(SICI)1099-1727(199623)12:3<183::AID-SDR103>3.0.CO;2-4.

[20] J. W. Forrester and P. M. Senge, "Tests for Building Confidence in System Dynamics Models," in System Dynamics, A. A. Legasto, J. W. Forrester, and J. M. Lyneis, Eds. Amsterdam: North-Holland, 1980.