Analysis of Offshore Wind Energy in Colombia: Current Status and Future Opportunities

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***Abstract*—Offshore wind energy is a sustainable and innovative energy source. However, its performance is extremely dependent on the local meteorology and oceanographic conditions. There are numerous opportunities as well as challenges to generate energy on a commercial scale in Colombia. This work tries to set up a base for harnessing offshore wind energy, considering the integration into the Colombian grid to offshore wind energy and the cost compared with the current system. The roadmap of the future of offshore wind energy in Colombia must be to fulfill three primary objectives identify the best opportunities for harnessing the offshore wind resource, to improve the investment in resources, and to reduce carbon dioxide emissions. This study provides specific knowledge about opportunities and challenges of offshore wind energy in Barranquilla, Colombia, through both technical and economic aspects.**

Keywords—Offshore wind energy; techno-economic analysis; wind power density; Weibull distribution; energy storage; Colombia

I. INTRODUCTION

Renewable energy in Colombia has been increasing at a rapid pace during the last two years. In 2018, the Colombian electricity portfolio from renewable energy was 50 MW, which corresponded to approximately 1% of the total electricity; in 2019, the portfolio corresponded to 1.5% (or 180 MW), and in 2020 it reached 1500MW. By 2022, it is expected to reach 10% of the Colombian electricity portfolio, reaching 2500MW [1]. To maintain the increase in the energy transition route, the electricity sector needs to develop additional generation capacity. On the other hand, Colombia is a country with one of the lowest carbon emission index globally [2]. However, it would not be exceptional to reduce its carbon dioxide (CO2) emissions by 20% by 2050 [3]. Colombia is also one of the most vulnerable countries to climate change and weather phenomenon like "El Niño", which lowers the level of sea drastically affecting the generation of energy from hydroelectric power systems. Colombia is working according to an important strategic plan for low carbon development (ECDBC) which has been implemented by a short, medium- and long-term development planning program and supported by several departments such as the Department of Energy and the Department of Environment from this same country [3], [4].

This strategic plan seeks to contribute to national, social, and economic development without causing an increase in the growth of CO2 emissions. Currently, renewable energy sources supply a small part (2%) of Colombia's general power generation with non-conventional resources such as solar, wind, and natural gas. However, this country still is not considering offshore wind energy projects [5]. It is necessary to assess the opportunities and challenges that the inclusion and diversification of sources, such as offshore wind energy, can cause in Colombia. By starting outlining a plan for offshore wind energy, it is expected that a more inclusive and diversified decision making will be implemented [6]. Also, knowing the opportunities and challenges of offshore wind energy in Colombia could accelerate the process to formulate economic plans to reduce carbon dioxide emissions by 2050 [3]. It would increase the non-conventional power system to supply electricity satisfying energy demand for the future of Colombian society. One of the advantages of Colombia is the availability of the coastal line, where some studies have been carried out to identify the potential of wind resources to generate electricity through the establishment of offshore wind farms to use the abundant wind resource in the Caribbean. Therefore, it is necessary to consider factors that affect or make viable the decision of inclusion of offshore wind energy in Colombia. Predominant factors that allow the development of offshore wind energy in this country can be political, technical, and economical.

The purpose of this study is to explore the opportunities and challenges at a technical and economic levels to include offshore wind energy to Colombia's energy needs. [6], [7], [8]. The motivation to do this study is to contribute to the knowledge of a different renewable energy source to provide detailed information for inclusion in the future of energy transitions. It would be helpful to use wind potential in the Colombian area of the Caribbean Sea [5], [6].

II. OFFSHORE WIND ENERGY OVERVIEW IN COLOMBIA

Offshore wind energy applies to an environment that depends on several factors. For example, Germany has had an important advance in the inclusion of offshore wind energy due to the characteristics that make it appropriate for the installation of technology. One factor is the depth of the sea near the coast. When offshore wind energy and onshore wind energy are compared, it is necessary to keep in mind the dependence of the natural resources, for example, the speed of wind in a region, which may or may not respond to the operating conditions [2], [7], [8], [9]. It is essential to establish a relationship between the availability of resources and the maturity of offshore wind energy technology in terms of cost-efficiency, highlighting that the availability of offshore wind energy should take advantage of wind energy progress because of the maturity of wind energy which had been possible over time. Furthermore, there is a relationship between technology and politics because a government should support research projects and experimental facilities to achieve a faster evolution for this technology. In the same way, technology can support political processes [9]. There is no doubt that the United Kingdom has a very strong installed base of offshore wind energy from a decade ago. Therefore, the United States, as part of the developed countries, has invested efforts to get a similar position in the market of this technology and has also invested great efforts to implement this technology since 2013 [10].

Offshore wind technology is an excellent opportunity to contribute to the reduction of carbon dioxide emissions and to supply power demand in the country. Nowadays, a considerable amount is supplied by offshore wind farms in the United States. This has added value to the country's energy portfolio and has increased the level of maturity of the offshore wind technology. Some countries, which have previously installed onshore turbines, are determined to adopt offshore wind farms. India has high offshore wind energy potential, which can be utilized along its vast coastline [10].

Offshore wind energy can be managed differently depending on the country and the strategic plan's policies. The implication of this technology includes the less expected impact on the environment compared with the onshore wind farm, but offshore wind energy is more expensive due to maintenance requirements, as well as support of the government of the country that has resources for the inclusion of offshore wind energy technology [2], [11]. Also, subsidies related to the economic incentives set by governments to promote a specific energy generation technology, modifying the supply and demand of the market [6], [9], [12]. Previous studies have estimated some marine sources such as offshore wind, wave, and tides. In Latin America can be utilized these kinds of sources in Colombia, Venezuela, Argentina, Uruguay, and the southern and northern Brazil coasts, east of North America, southeastern Asia, northwestern Europe, and in the Mediterranean Sea, The South Pacific Ocean off Oceania and on the Moroccan coast. Of the mentioned zones, the north-northeast of South America shows the highest resource stability. An article published by Rueda-Bayona et al. (2019) suggests that a preliminary study called “Assessment of the Marine Power Potential in Colombia” is necessary to enhance the knowledge about the technical, and financial feasibility studies for installation and operation of the offshore wind energy in Colombia [6], [13]. Another study by Osorio et al. (2011) established that Colombia has a great wind power potential on the coast near to Barranquilla [5].

The Colombian power system has a big dependence on hydropower production; approximately 70% of the installed capacity of the country is made up of hydropower plants due to the fact that Colombia is one of the countries with the greatest water wealth both globally and in Latin America [3], [5], [14], [15]. In accordance to the mean monthly wind speed over the year in Barranquilla reported in 2019, figure 1 demonstrated that, on average, the most wind is seen in January, and on average, the least wind is seen in October.

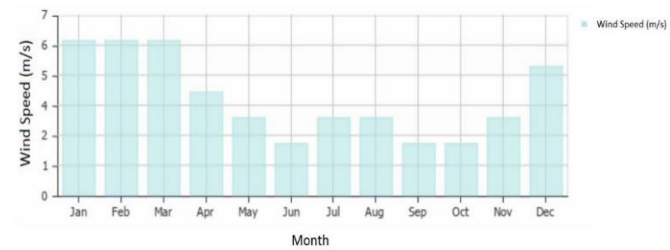

Fig. 1 Average Wind Speed in Barranquilla-Atlántico, Colombia - Data from the nearest station [16]

The study's significance is based on the qualitative and quantitative aspects of the opportunities to generate sustainable strategies in the inclusion of renewable energy according to the natural resources of Colombia.

This study seeks to answer the following research questions:

- How to assess the offshore wind energy potential on the coast of Colombia?
- How to integrate more renewable energy into Colombia’s energy portfolio using offshore wind?

III. AN ENGINEERING VISION OF OFFSHORE WIND ENERGY IN TWO CITIES

Wind speed and the mean wind power are two factors extremely important to know the potential of wind energy in a certain location [17], [18]. Basically, moving air molecules that have mass, though not much, are the composition of the wind. Therefore, a moving object with mass carries kinetic energy in an amount that is given by the equation:

$$KE = \frac{1}{2} m V^2 \quad (1)$$

where KE is the kinetic energy and is given in joules. the Mass is measured in kg, the velocity is given in m/s. Air has a known density ρ in (kg/m3) so the mass flow rate of air hitting an offshore wind turbine (which sweeps a known area (m2)) each second is given by the following equation:

$$\dot{m} = \rho A V \quad (2)$$

So that, the power which is given in energy per second, in the wind hitting an offshore wind turbine with a specific swept area is given by the mass per second calculation into the standard KE equation (1) resulting in the equation (3) [18]:

$$P = \frac{1}{2}\rho A V^3 \quad (3)$$

This research used the Reanalysis database of the NARR project to determine the wind power density for two locations along the coast of Colombia. Barranquilla and La Guajira were the two selected cities [19], [20]. The data was collected from the database of the study of Rueda Barona [6]. This data was used to obtain information about the wind velocity and direction from January 1979 to December 2015 at 10 m of elevation for the two strategic locations [19]. This historical data was first converted into a histogram. The histogram categorized each of the wind speeds over that time period in terms of bins. The bin size for the histograms at each site was chosen to be 1 m/s. The bin range was chosen to be 0 to 20 m/s. This determined the total instances of wind speeds within a particular bin to construct the histogram.

The total instances were then converted into a frequency to determine the percent of time that the wind speed occurs in a bin. This historical data was then used to find the Weibull distribution [17]. The Weibull distribution is the most widely accepted function in the wind industry. This is because the International Electrotechnical Commission (IEC) recommends this function to estimate the wind speed data (via IEC standard 61400-1 for large wind turbines).

The Weibull distribution provides the most accurate representation of the wind speed histograms. The Weibull distribution probability density function (PDF) was utilized to determine the best fit of the histogram's frequency data. The PDF was then defined in terms of its shape and scale factor to estimate the best fit to the histogram data. Figure 2 showed the Weibull distribution in Barranquilla that exceeded the data, representing that this city is the best option compared to the city in Figure 3 which showed that the data exceeded the Weibull distribution.

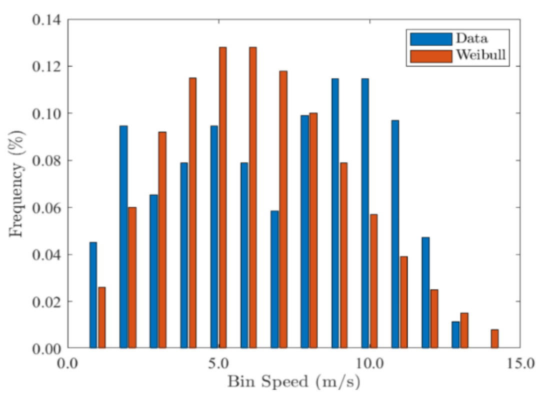

Fig. 2 Wind Speed Distribution based on the collected data and the best fit Weibull distribution in Barranquilla

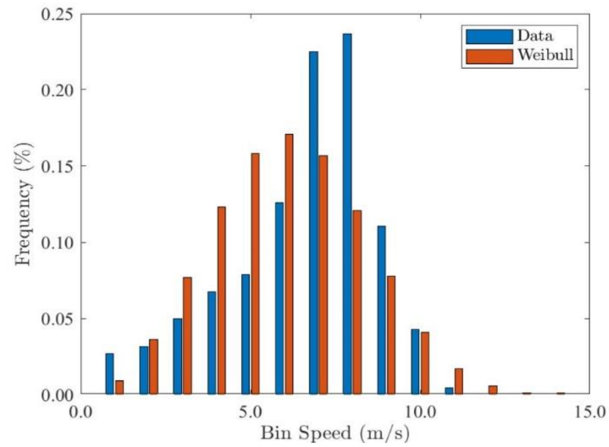

Fig. 3 Wind Speed Distribution based on the collected data and the best fit Weibull distribution in La Guajira

This information was then used to determine the wind power density at each site [17], [18].

The wind power density (WPD) is generally defined as:

$$WPD = \frac{1}{2}\rho V^3 \quad (4)$$

where WPD is given in Watts per square meters, ρ is the air density (1.225 kg/m3), and V is the wind speed in meters per second. By increasing the WPD, the site is increasingly more suitable for wind project development. By taking this equation, multiplying it by the frequency of the bins, and replacing the wind speed with the bin speed in the histogram, the WPD at each bin can then be determined. By summing up each of these bins, the total WPD at the site can, therefore, be estimated. To quantify the wind power density in Barranquilla the shape factor, scale factor, and average velocity (vave) were defined respectively as:

$a = 2.25$

$b = 7.177272\, m/s$

$vave = 6.35712\, m/s$

TABLE 1 DATA USED TO QUANTIFY THE WIND POWER DENSITY (WPD) IN BARRANQUILLA

Bin	Frequency	Data	Weibull	WPD-Data (W/m^3)	WPD-Weibull (W/m^3)
0	0	0	0.000E+00	0.000E+00	0.000E+00
1	20	0.045	2.600E-02	2.700E-02	1.600E-02
2	42	0.095	6.000E-02	4.600E-02	2.940E-01
3	29	0.065	9.200E-02	1.080E+03	1.514E+03
4	35	0.079	1.150E-01	3.090E+03	4.524E+03
5	42	0.095	1.280E-01	7.242E+03	9.804E+03
6	35	0.079	1.280E-01	1.043E+04	1.699E+04
7	26	0.059	1.180E-01	1.230E+04	2.480E+04
8	44	0.099	1.000E-01	3.108E+04	3.141E+04
9	51	0.115	7.900E-02	5.129E+04	3.518E+04
10	51	0.115	5.700E-02	7.035E+04	3.527E+04
11	43	0.097	3.900E-02	7.895E+04	3.193E+04
12	21	0.047	2.500E-02	5.006E+04	2.627E+04
13	5	0.011	1.500E-02	1.515E+04	1.971E+04
14	0	0	8.000E-03	0.000E+00	1.354E+04
15	0	0	4.000E-03	0.000E+00	8.539E+03
16	0	0	2.000E-03	0.000E+00	4.939E+03
17	0	0	1.000E-03	0.000E+00	2.631E+03
18	0	0	1.000E-03	0.000E+00	1.296E+03
19	0	0	1.000E-03	0.000E+00	5.830E-01
20	0	0	4.960E-05	0.000E+00	2.430E-01
	0	0			
	444			3.310E+05	2.684E+05

To quantify the wind power density in La Guajira the shape factor, scale factor, and average velocity (vave) were defined respectively as:

$$a = 3$$

$$b = 6.843388\, m/s$$

$$vave = 6.1110053\, m/s$$

TABLE 2 DATA USED TO QUANTIFY THE WIND POWER DENSITY (WPD) IN LA GUAJIRA

Bin	Frequency	Data	Weibull	WPD-Data (W/m^3)	WPD-Weibull (W/m^3)
0	0	0	0.000E+00	0.000E+00	0,00E+00
1	12	0.027	9.000E-03	1.600E-02	5.700E-03
2	14	0.031	3.600E-02	1.540E-01	1.790E-01
3	22	0.049	7.700E-02	8.190E-01	1.280E+00
4	30	0.068	1.230E-01	2.648E+03	4.808E+00
5	35	0.079	1.580E-01	6.031E+03	1.213E+01
6	56	0.126	1.710E-01	1.669E+04	2.272E+01
7	100	0.225	1.570E-01	4.732E+04	3.304E+01
8	105	0.236	1.210E-01	7.416E+04	3.802E+01
9	49	0.110	7.800E-02	4.928E+04	3.481E+01
10	19	0.043	4.100E-02	2.621E+04	2.531E+01
11	2	0.005	1.700E-02	3.672E+03	1.451E+01
12	0	0	6.000E-03	0.000E+00	6.496E+00
13	0	0	1.000E-03	0.000E+00	2.243E+00
14	0	0	1.000E-03	0.000E+00	5.890E-01
15	0	0	5.620E-05	0.000E+00	1.160E-01
16	0	0	6.746E-05	0.000E+00	1.600E-02
17	0	0	5.951E-05	0.000E+00	1.790E-03
18	0	0	3.792E-05	0.000E+00	1.300E-04
19	0	0	1.714E-05	0.000E+00	7.203E+00
20	0	0	5.402E-05	0.000E+00	2.647E+00
	444			2.260E+05	2.060E+02

IV. RESULTS

Barranquilla, compared to La Guajira, reported the highest monthly mean of wind power density. The expansion plan for transmission and generation of electrical energy in Colombia was studied. This plan covered the years 2015-2029 [3], [21]. The map with the current interconnection and transmission lines of the country and the map with future interconnections were obtained by Global Energy Network Institute as shows Figures 4 and 5 [22], [23]. The Colombian electricity system has interconnections that allow electricity exchanges with Ecuador and Venezuela.

Fig. 4 Current interconnections and transmission lines in the Colombian grid [22]

When the graph was approached, the 220kV substation installed in Barranquilla was identified. This substation could be connected to the transmission line of the offshore wind energy farm. Figure 2 shows a zoom-in of figure 3 to identify all the transmission lines in the local grid in Barranquilla.

Fig. 5 Current interconnections and transmission lines in the local grid in Barranquilla [22]

On the map of interconnections, an oil field and a gas field were observed near La Guajira [35]. However, Colombia does not yet have oil exploration or exploitation activities with fracking. A high court listens to advocates and opponents amid a significant debate between lawmakers, activists, the government, and citizens before deciding whether to allow the technique to be used.

Fig. 6 Future interconnections and transmission lines to use with oil and gas fields [23]

For future scenarios, Colombia considered an interconnection between the Cerromatoso substation and the Panama II substation. Figure 6 showed the branch that supports this electrical expansion.

Fig. 7 Interconnections between Colombia and Panamá substations [24]

System Advisor Model (SAM) was used to simulate a scenario of offshore wind energy in Barranquilla.

SAM is an engineering tool designed for the techno-economic analysis of renewable energy projects [25]. Basically, SAM is a decision-making tool for project developers, financial analysts, policymakers, and energy researchers. This research used SAM to model the offshore wind farm. The first step was to define

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the wind resource using characteristics of the Weibull distribution.

The Weibull distribution represents the wind resource as a statistical distribution characterized by a single average annual wind speed and Weibull K factor [17], [18], [25]. SAM was used to determine Weibull probability and turbine energy. The Weibull PDF determines the probability that a given wind speed value will occur over a given period:

$$f(V) = \frac{k}{\lambda^k} V^{(k-1)} e^{-\left(\frac{V}{\lambda}\right)^k} \quad (5)$$

Where

$f(V)$ = Weibull wind speed probability distribution function

V = wind speed in m/s

k = dimensionless shape parameter

λ = scale parameter in m/s

Therefore, to get the wind speed Weibull distribution all wind resources characteristics were defined such as:

$$Average\ annual\ wind\ speed = 6.357\, m/s$$

$$Reference\ height\ for\ wind\ speed = 10m$$

$$WeibullK\ \ factor = 2.25$$

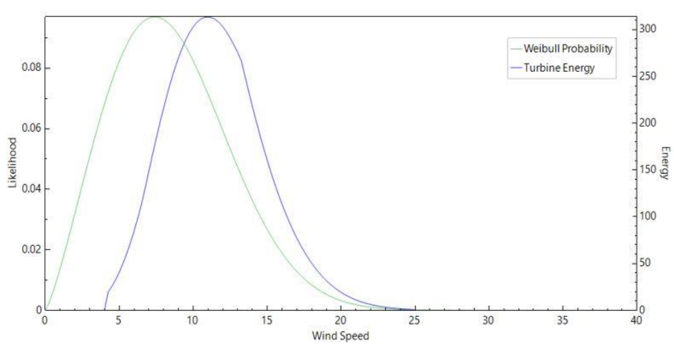

Fig. 8 Wind speed Weibull distribution and turbine energy distribution in SAM for Barranquilla

Figure 9 indicated the location of the offshore wind farm project with the 25km of approximate distance between offshore and substation of 220kV.

Fig. 9 Distance between the offshore wind farm and the 220kV substation in Barranquilla [26]

Given the information in Table 3 was implemented the project in SAM.

Table 3 Data on the specifications of the proposed offshore wind project in Barranquilla, Colombia

Name	Specifications
Project Name	Offshore wind energy in Barranquilla Colombia
Size of project (MW)	360MW
Type of turbine	Siemens SWT-6.0-154
Size of the turbine	6MW
Year of start of commercial operation	2075
Distance to shore	25km
Water depth	15 to 100 m
Type of support structure	Monopile
Turbines	60
Minimum capacity factor	25.2%
Maximum capacity factor	36.9%

In accordance to the information about Siemens' SWT-6.0-154, the offshore turbine's power curve was inputted into SAM. The rated wind speed was 13m/s and was defined based on the maximum tip speed ratio [25], [27].

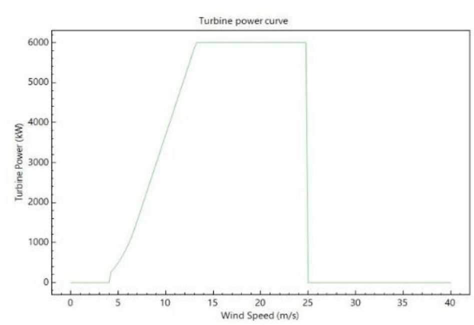

Fig. 10 Turbine power curve in SAM

According to the turbine layout map in Fig. 11, the total project area was calculated as $6{,}000 * 11{,}000 = 66{,}000{,}000m^2$.

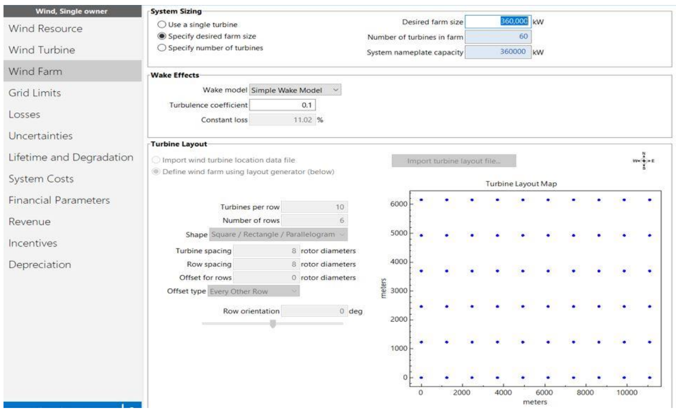

Fig. 11 The proposed offshore wind project layout map in SAM

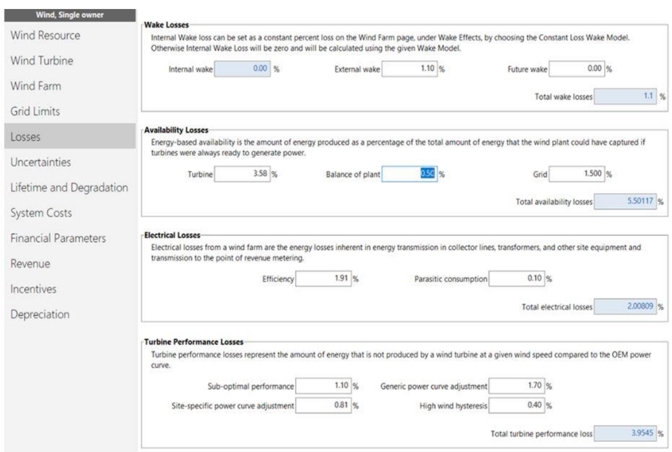

Fig. 12 Offshore wind farm wake, availability, electrical, and turbine performance losses in SAM

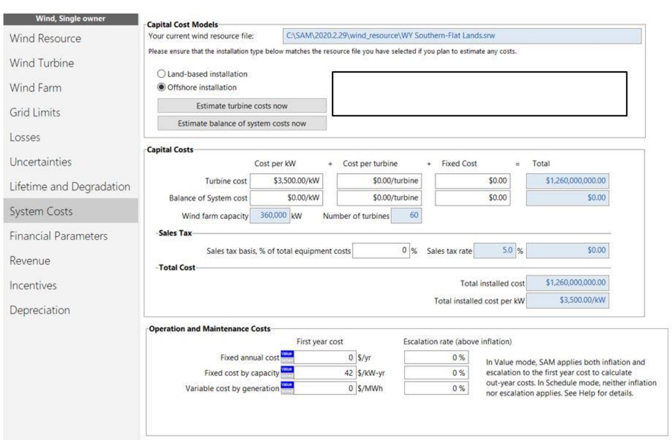

Fig. 13 Cost model utilized in SAM

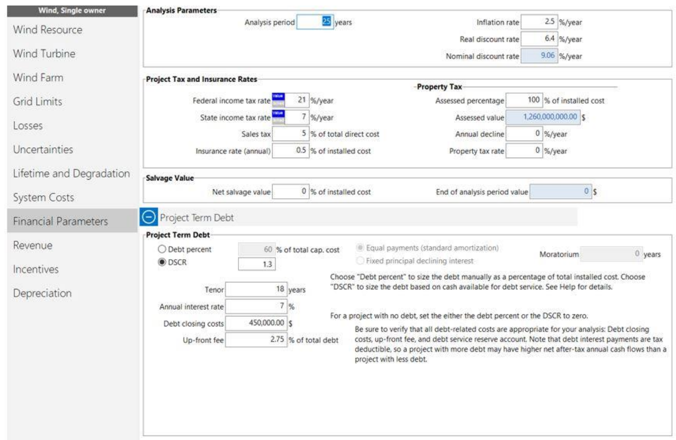

Fig. 14 Financial parameters in SAM to define the economic analysis

The capacity factor may theoretically vary from 0 to 100 percent. However, they usually range from 20 to 70 percent and mostly be around 25-40 percent. This project, with a rated capacity of 360 megawatts and an efficiency factor of 0.37 percent, would be expected to produce as follows: 365 * 24 * 360000 (kW) * 0.37 = 1,166,832,000 kilowatt-hours per year. This calculation assumes wind availability at 24 hours a day all year round. In practical application, this does not happen. SAM used the NREL wind maps to adjust your time figures for a more accurate location-specific figure. This value was 1,164,893,312 kilowatt-hours per year.

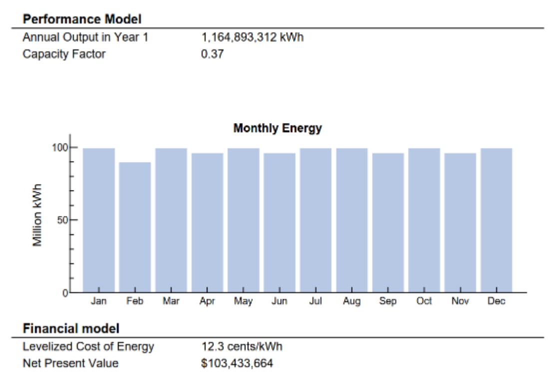

Fig. 15 Monthly and annual energy output as well as the capacity factor for the project in the first year

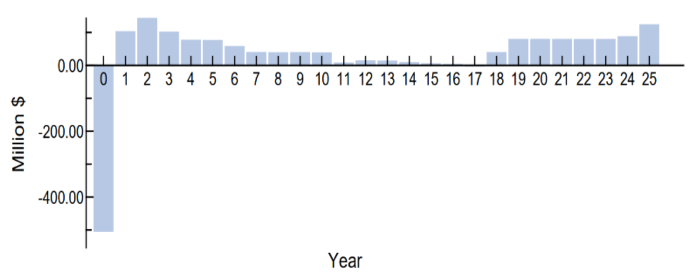

Fig. 16 After-tax Project cash flow in SAM

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A. Energy Storage System

The use of ESS has been extended to offshore wind energy. ESS can be utilized to store electricity during a period of low market prices. Therefore, ESS can reduce the gap between peak and off-peak periods resulting in greater efficiency. During the self-discharge and large price variations, the electricity is not stored for long periods. The economic viability of an ESS in the offshore wind project is dependent on the system's profitability. The total cost for the offshore wind farm can be determined in combination with an ESS [28]. The key performance indicator is the net present value (NPV) of the project's cash flow. In the analysis, this project only considered onshore locations and average capacities of the ESS. The type of ESS considered in this study was a lithium-ion battery. Based on previous studies which have determined the SUM model with prices and wind data for New York during 2010-13, the researchers evaluated four designs of offshore wind and battery storage systems such as an offshore wind farm without BESS, an onshore BESS, an offshore BESS, and a hybrid. A system that BESS uses both on land and at sea - to assess the impacts of the battery system location on its overall profitability [28], [29]. Basically, one of the most important attributes of the "SUM" model is that it involves degradation as a sum of the capacity fades in the battery cells produced by the battery charging and discharging process, in addition to the deterioration in time function, regardless of battery usage. According to these criteria, the battery is cycled if the income supports the costs of loss of capacity. In addition to adding other different decision factors, such as wind reduction, cable size, and BESS shipping, this research concludes that the increased revenue potential and may offset some of the costs related to degradation occurs when installing the system of lithium battery grounded while operating within its state of charge window [28].

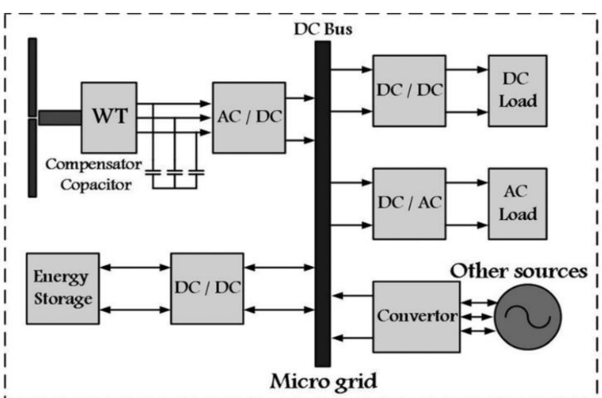

Fig. 17 Topology of the connection between the offshore wind energy and energy storage

V. Discussion and Prospects

After getting the financial model in SAM of the offshore wind energy farm in Colombia, the annual output was 1,164,893,312kWh. This value represented the capacity of the turbines array working for the first year. The capacity factor was calculated to be approximately 37%. The levelized cost of energy (LCOE) was 12.3cents/kWh it measures lifetime costs divided by energy production and calculates the present value of the total cost of building and operating a power plant over an assumed lifetime. LCOE was useful because it could allow the comparison of different technologies that the Colombian government could implement in Barranquilla (e.g., wind, solar, natural gas) of unequal life spans, project size, different capital cost, risk, return, and capacities [30]. The net present value (NPV) of the project was $103,433,664. The results of this project indicate that the Colombian government should consider installing an offshore wind energy farm because of the positive economic impact it would have on the country. Not only is the NPV positive, but the sensitivity analysis shows that it remains positive under a wide variety of conditions including varying the discount rate, costs, and quantity of electricity generated. There are several grant programs in the U.S. that could potentially fund some or all the initial capital costs. It should be re-emphasized that SAM is one decision-making tool among many. Various positive externalities such as an offset of future CO_2 emissions, reduced pollution, increased energy security and negative externalities such as possible bird or bat deaths. There is the possibility of the inclusion and diversification of renewable energy on coasts around the world, which can be supported by governments. Also, investment decision making about offshore wind energy requires significant capital. Still, it may have low operating costs compared with technologies based on fossil fuels, which do not require too much capital, but the cost of operation is high [25].

The essential advantage that offshore wind energy has is the speed of wind resources in the sea, where the wind speed is usually very high [3], [10]. Other advantages presented by the technology are related to the fact of being installed in suitable free areas in the sea. However, the technology requires more installations. This technology gives many benefits to the environment because can reduce carbon dioxide emissions, and also there are many benefits to the population due to the reduction of the visual and auditory impact, as well as the ease of transport of wind turbines which can allow more generation per install unit [5], [6], [9]. The disadvantage of offshore wind energy technology is the cost of the authorizing and detail engineering process, as well as the building and operation phases, which require a high price [25]. Furthermore, there are not usually under the sea electrical infrastructures that connect the highest wind resource areas with the consumer centers, leading to the construction of transmission lines and electrical networks. In other cases, the existing power system needs to be strengthened.

A greater body of water is the Caribbean Sea which is delimited by Colombia, Venezuela, and Panama to the south, to west Costa Rica delimits it, Nicaragua, Guatemala, Honduras, and Belize; as the Greater Antilles Cuba, Jamaica, Dominican Republic, and Puerto Rico, delimit it to the north, the Lesser Antilles does it to the east. Colombia has 928,660 km^2 of oceans

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and 2,900 km of coastline, and it is a unique South American country that has coasts on the Pacific Ocean and the Caribbean Sea. A big population lives in the Caribbean zone because there are main cities located along the coast. The Colombian power system has a big dependence on hydropower production, approximately 70% of the installed capacity of the country is made up of hydropower plants due to that Colombia is one of the countries with the most significant water wealth both globally and in Latin America [5], [12].

A. *Opportunities for offshore wind energy in Colombia*

Wind speed in Barranquilla, Colombia, is significantly high and less unstable caused by the roughness of the Caribbean Sea surface, which is smaller than land surfaces [3], [6].

According to the Colombian energy market, the Colombian government could implement a tax reduction or exemption to investors of the project to support the inclusion and diversification of offshore energy farms [12], [31].

Offshore energy technology could be implemented for several purposes; one of these important purposes, when applied to the environment, could be to reduce carbon dioxide emissions in the country. Therefore, Colombia could accomplish the goal of reducing 20% of carbon dioxide emissions by 2050 [3].

B. *Challenges of offshore wind energy to Colombia*

The main challenges of offshore wind energy are construction and maintenance costs. Furthermore, the offshore turbines need an efficient and resilient structural design to face critical conditions in the sea. Colombia has analyzed the development of political proposals to boost renewable energies as an opportunity of the energy transition. Every proposal was thought in other renewable energy sources such as solar, wind energy, and biomass. It could represent a challenge to offshore wind energy because offshore is a relatively new technology compared with other sources that the Colombian government, private, and public sector knows. The private and public sector facilitates the accomplishment of renewable energy projects. The private sector must focus on supply resources for the implementation of the project, while the public sector must focus on determining the right regulations to increase energy services around the country, stimulating the development of other renewable energy systems in Colombia [32].

Colombia has been working on the development of political proposals to boost renewable energies as an opportunity of the energy transition. Offshore wind energy in Colombia allows an opportunity to reduce the dependency of hydropower, which is a good option due to the level increase in the sea caused by climate change and the presence of the phenomenon both El Niño and La Niña [5]. Although solar, wind, and biomass currently account for only 2% of the total generation capacity in the country, some strategic plans point to an increase of these primary energy resources in the next decade, either via offshore wind energy or other renewable energy [31].

VI. Conclusions

The installation of an offshore wind farm in Barranquilla is more expensive than the onshore wind farm in the same place. It is more expensive due to the cost of turbines, O&M, foundation, and transportation. However, the cost per kWh could be cheaper compared with the cost produced by onshore wind farms and hydropower. It was determined according to the information on the cost of the electricity in Barranquilla. Nonconventional energy projects compete in auctions that award long-term contracts specifically tailored to these technologies. In the future of the energy market contracts could be offered to offshore wind energy in Colombia. Contractual arrangements facilitate access to low-cost debt and favor offshore wind energy over the next decade. Colombia's annual electricity consumption is approximately 70,000 GWh/year, and for the next decade, according to UPME's estimates, an average annual increase of 2% is expected. Therefore, to supply this higher estimated consumption for the next decade, it is necessary to continue expanding the country's energy infrastructure, generation as well as transportation. This must be planned years in advance. Technical and economic factors allow understanding the strategic aspects of offshore wind energy as a part of the distributed generation in Colombia. Offshore wind energy could comprise an important percent of the Colombian power generation capacity in the future and support the electrical expansion in South America. For the next decade, Colombia is expecting that the power demand will increase by approximately 2% per year. A major challenge may be to demonstrate the potential for wind-based generation at the commercial level, thereby facilitating investments that will capture the relatively large wind energy potent identified in the country.

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