Potential of renewable energies from ocean resources in the Colombian Caribbean

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I. Introduction

THE generation of energy from renewable sources and with oceanic resources has great advantages, starting from the spectrum of different technologies available today. Each of these technologies harnesses a different potential that, in general terms, indicates a significant opportunity of exploitation in the Colombian case. This is because the country has an interesting maritime platform, with coasts in the Pacific and Atlantic oceans. This points to a diversity of behavior not only of the waters, but of other resources such as wind and solar radiation.

Considering the available resources, we identified the main locations for self-generation of energy related to the operation and infrastructure of Ecopetrol S.A. in the Colombian Caribbean, based on their proximity to both the coast and infrastructure of interest. This with the intention of using renewable energy in specific processes, either in the current operation of the company or in future infrastructure projects.

This work presents a methodology that can be applied in different locations as an initial guide for renewables technologies selection, obtaining a preliminary analysis not only of the resource, but of the way to harness it and the costs involved. For the resource assessment, the technical potentials were estimated in determined locations with offshore wind, floating solar, wave, tidal, saline gradient and thermal gradient technologies. In the process, relevant energy converters were chosen according to the site conditions, in order to compare the current technological development of each technology. In this estimation process, it was possible to identify different parameters that allow the comparison of technologies, so that the implementation of some of them can be prioritized over others. In addition, a preliminary costs analysis was carried out in order to observe the economic scenario of each implementation.

A. Sites of interest

We selected sites distributed at different distances from the coast in the Colombian Caribbean and that have diverse characteristics that allow evaluating the behavior of the considered technologies.

II. Methods

The technical potentials of the different technologies are estimated using a similar methodology.

Initially, the information is collected from the relevant databases that contain the description of the resource to be evaluated: wind speed, solar irradiation, current speed, height and period of waves, thermal gradient of the water column and saline gradient in the locations of interest. After quantifying and describing the resource present at the sites, the reference energy converters are chosen for each technology. Finally, the energy that each equipment can harness from the available energy resource is analyzed, describing the performance at the sites of interest and creating a preliminary costs analysis.

A. Input data

The input data used in the evaluation of each of the technologies are presented below.

Wind offshore

We used the open access package '*ERA5 hourly data on single levels from 1979 to present*', which is a global reanalysis data set with hourly climate information and spatial resolution of 0.25°x0.25°. In particular, the period 2009-2021 of the eastward and northward components of the 100 m wind was used to calculate the magnitude and direction of the wind velocity.

On the other hand, the technology chosen to describe the energy use is a 5.5 MW offshore wind turbine with a diameter of 158 m and installed at a height of 100 m.

Floating solar

Also in this case, we used the ERA5 reanalysis data for the period 2009-2021, using the variables 'mean surface downward short-wave radiation flux', 'sea surface temperature' and the components of the 10 m wind speed.

On the other hand, the technology used to harness the energy resource corresponds to 390 W panels and 19.6% efficiency.

Wave energy

We work with a data set from the *Global Ocean Waves Reanalysis WAVERYS*, with spatial resolution of 0.2°x0.2° and temporal resolution of 3 hours, particularly, with the variables 'spectral wave height', 'spectral moments', 'wave period' and 'peak wave period' in the interval 2010-2020.

On the other hand, the technologies used to harness energy are a 250kW buoy-type device that starts generating at 1.5 m wave height and 6 s wave period, and another 750kW attenuator-type converter for which the minimum operating values are 1 m height and 5.5 s period.

Tidal Energy

The forecast data package *Global Ocean 1/12° Physics Analysis and Forecast updated Daily* was accessed with a resolution of one hour and 0.083°×0.083°. The chosen interval was from 01-01-2020 to 07-31-2022 of the northward and eastward components of the total current velocity.

On the other hand, the considered technologies are a commercial one, horizontal axis turbine made up of 6 turbines of 70kW each for a total of 420kW rated power and a rotor diameter of 6.4 m, and one under development, with a hybrid vertical axis turbine since it is made up of designs of 0.2 m and 1 m diameter with a rated power of 146W.

Ocean thermal energy conversion (OTEC)

Also in this case, we use the ERA5 reanalysis data in the period 1993-2021, using the variable 'potential seawater temperature', with a resolution of one day and 0.083°x 0.083° (horizontal), 1 – 450 m (depth).

On the other hand, the chosen technology corresponds to a floating plant with a rated power of 1 MW that has a net efficiency of 1.71%.

Salinity Gradient

Also in this case, we used ERA5 reanalysis data in the period 1993-2021, using the variables 'potential seawater temperature' and 'salinity', with a resolution of one day and 0.083°x0.083° (horizontal), 1 – 450 m (depth).

On the other hand, the chosen technology corresponds to a chemical plant of RED technology.

B. *Evaluation criteria*

The main evaluation criteria for the sites of interest in the Colombian offshore are described.

On-site installation

It mainly refers to the depth of installation on site, a determining factor in many cases when choosing the appropriate technology. For some applications it extends to the distance to the coast and the height of the waves.

On-site availability

Allows the estimation of the availability of the resource evaluating the variables directly associated with the resource or the power density of the technology.

On-site variability

It is quantified using coefficients of variation or deviations from established references for the technologies, being an indicator of the resource stability and variations that can be expected during the generation.

Installed capacity

It works as a reference between sites and later between technologies, indicating the installed capacity for each scenario.

Capacity factor

It is a performance indicator, particularly relevant when comparing different energy converters and renewable energy technologies.

Nominal resource

Records the value of the nominal resource that is necessary for the proper functioning of each of the technologies.

Technology Readiness Level (TRL)

Indicates the current maturity of the technology, based on the TRL that corresponds to it.

III. RESULTS

The technical evaluation of the offshore resource potential for the selected sites is shown in the tables included in this section for each technology, according to the criteria previously described.

The results for offshore wind power are shown in Table I, where it can be seen that those points where it would be possible to use fixed foundations are 5, 6 and 7. Regarding the resource available in the locations, there is a very low availability in 2, while the other points show significant potential, and in terms of variability, the lowest values correspond to 1 and 6. Regarding the technology, a greater maturity is assigned to fixed foundation applications. As the desired nominal resource of the technology, the range 8-16 m/s is indicated, and in terms of the capacity factors obtained, that of 2 is particularly low, and those of 1 and 6 are significantly high.

The results for floating solar are found in Table II, where point 6 shows the highest availability of the resource due to the optimal site conditions for the implementation of FPV systems. For location 5, although the availability of the resource is not among the highest values, the

TABLE I
EVALUATION RESULTS FOR WIND OFFSHORE

Charact.	Variable	1	2	3	4	5	6	7
Site	Depth (m)	609	2109	837	309	44	44	49
Resource	Availability (m/s)	10.57	4.35	8.23	8.75	8.10	10.44	8.77
	Variability (%)	25	48	40	36	35	26	43
Techno-logy	Installed capacity (MW)	5.5	5.5	5.5	5.5	5.5	5.5	5.5
	Capacity factor (%)	62.4	7.6	43.3	47	41	61.4	43.7
	Nominal resource (m/s)	8-16	8-16	8-16	8-16	8-16	8-16	8-16
	TRL	8	8	8	8	9	9	9

TABLE II
EVALUATION RESULTS FOR FLOATING SOLAR

Charact.	Variable	1	2	3	4	5	6	7
Site	Depth (m)	701	2316	837	173	40	21	45
	Distance to coast (km)	38	66.51	32	50	5	6	18.7
	Max. wave height (m)	8	7.2	6	8	5.5	6	6
Resource	Availability (kWh/m²/d)	6.18	5.6	5.98	6.04	5.73	6.26	5.71
	Variability (%)	7.66	9.39	5.95	9.12	5.35	7.12	11.12
Techno-logy	Installed capacity (MW)	0.205	0.243	0.224	0.224	77.47	0.201	0.243
	Capacity factor (%)	17.85	15.65	16.93	17.06	16.45	18.35	16.12
	Nominal resource (W/m²)	839	766	828	836	801	854.6	791
	TRL	8	8	8	8	7	7	8

TABLE III
EVALUATION RESULTS FOR WAVE ENERGY

Charact.	Variable	1	2	3	4	5	6	7
Site	Depth (m)	609	2125	837	309	44	44	45
Resource	Availability (kW/m)	9.060	4.76	5.71	5.053	3.18	6.47	4.63
	Variability height (%)	13.8	49	25.34	16.56	17.73	12.44	27.73
	Variability period (%)	3.38	7.91	2.77	2.60	3.24	2.91	3.75
Techno-logy	Installed capacity (MW)	0.013	0.013	0.029	0.029	0.029	0.050	0.029
	Capacity factor (%)	5-10	5-10	25-40	25-40	5-10	5-10	25-40
	Nominal resource (m)	1.72	1.19	1.38	1.31	1.06	1.5	1.22
	Nominal resource (s)	6.25	6.51	6.12	6.01	5.79	5.87	6.35
	TRL	7	7	7	7	7	7	7

conditions of the site compensate for it, being the most suitable location for the implementation of FPV systems according to the results. Regarding the capacity factor, we observe values close to each other, obtaining the highest value at 6 and the lowest at 2.

The results for wave energy are shown in Table III, where it is recommended to use the buoy-type device in 1 and 2, and the attenuator type in the rest of the points. In addition, the order of priorities according to the ability to harness the wave resource is 6, 7, 1, 5, 4, 3 and 2.

The results for tidal energy are shown in Table IV, where the devices installation is feasible only at points 6 and 5 due to their depth, for the other cases a detailed study of the anchoring system for the installation of floating technologies would be required. Regarding availability, the points studied have low speeds compared to other areas of the world. We can also observe that the capacity factor in the two considered technologies does not reach the expected theoretical ranges, nor commercially proven values because the operating speeds required to work at rated power are higher than those of the sites.

TABLE IV
EVALUATION RESULTS FOR TIDAL ENERGY

Charact.	Variable	1	2	3	4	5	6	7
Site	Depth (m)	678	2125	837	173	36	31	45
Resource	Availability (m/s)	0,554	0,284	0,198	0,248	0,285	0,564	0,395
	Variability (%)	23,3	24,24	14,56	11,14	23,29	10,82	28,71
Techno-logy: Commer cial (C)	Installed capacity (kW)	420	420	420	420	420	420	420
	Capacity factor (%)	3,06	0,5	0,14	0,28	0,36	1,81	1,02
	Nominal resource (m/s)	2,3	2,3	2,3	2,3	2,3	2,3	2,3
	TRL	7	7	7	7	7	7	7
Techno-logy: Develop ment (D)	Installed capacity (kW)	0,146	0,146	0,146	0,146	0,146	0,146	0,146
	Capacity factor (%)	27,54	5,65	1,63	3,59	4,07	19,22	11,26
	Nominal resource (m/s)	1	1	1	1	1	1	1
	TRL	1	1	1	1	1	1	1

TABLE V
EVALUATION RESULTS FOR OTEC

Charact.	Variable	1	2	3	4	5	6	7
Site	Distance (km)	5.4	0	6.2	8.6	25.9	32.5	21.6
Resource	Availability (°C)	20.7	23.4	21.1	21.6	21.5	21.5	22.7
	Variability (°C)	1.6	1.1	1.9	1.8	1.8	1.5	1.4
Techno-logy	Installed capacity (MW)	1	1	1	1	1	1	1
	Capacity factor (%)	100	100	100	100	100	100	100
	Nominal resource (°C)	20	20	20	20	20	20	20
	TRL	6	6	6	6	6	6	6

TABLE VI
EVALUATION RESULTS FOR SALINITY GRADIENT

Charact.	Variable	1	2	3
Site	Distance (m)	6.4	3.0	2.1
Resource	Availability (g/L)	35.1	34.5	33.8
	Variability (g/L)	1.4	0.4	0.5
Technology	Installed capacity (MW)	1	20	150
	Capacity factor (%)	100	100	100
	Nominal resource (g/L)	36.1	34.5	33.8
	TRL	6	6	6

The results for OTEC are shown in Table V, where we observe that 2, 1, 3 and 4 (in that order) have the shortest distances to the point of interest. In particular, the technology is applicable exactly at site 2, so the costs associated with energy transportation are minimized to the maximum. It can also be seen that the results regarding the technology are the same for all points, showing no differentiation between sites for the technology variables.

The results for salinity gradient are shown in Table VI, where we observe that distances, resource, variability and installed capacity differ notably from each other, particularly due to the amount of fresh water available. In all three cases, 100% capacity factor is achieved with technologies that currently have a TRL of 6. We note that 1 is less favorable because it has greater distance and variability, although greater salinity.

IV. PRIORIZATION

The classification of the evaluated technologies is presented in this section.

A. Evaluation criteria

The main aspects that must be taken into account to compare the technologies from a technical point of view, and thus be able to determine an order of priority, are shown below.

Installation

The site plays an important role in determining the technology installed capacity considering the mechanism to attach or support the energy converters. This criterion can be evaluated through the installed capacity as a function of the site depth.

Resource Availability

This factor allows to evaluate the resource intermittency. One way to measure it, is through the effective operating time, taking into account the operation limits of each technology.

Resource Stability

Even within the operational range of the technology, a high variability of the resource can imply wear and malfunction of the devices. One way to evaluate this criterion is by calculating the coefficients of variation of the resource from its historical behavior.

Installed capacity

The rated capacity of a plant for self-generation of energy responds to the energy needs for which it was designed. In many cases, the available devices have capacity limitations, so considering this parameter it is possible that one technology stands out over another.

Capacity factor

The capacity factor is a good indicator to measure the suitability of a technological solution in a site of interest, evaluating the performance of the conversion system based on its optimal behavior.

Relation of the available resource and the technology nominal resource

Comparison of the average behavior of the resource with the nominal value for which the technology was designed.

Technological maturity

The TRL is used to indicate the development status of a technological solution.

Required area

Although no limitations are assumed regarding the availability of the surface for the installation, this criterion may be important when evaluating requirements and costs related to foundations, mooring and anchoring.

TABLE VII
PRIORIZATION RESULTS

	Factor	Weight	WO	FS	WE	TE	OTEC	SG
Site 10%	Installation	0.1	3	4	4	3	4	3
Resource 20%	Availability	0.1	4	4	2	2	4	4
	Stability	0.1	2	3	3	2	5	3
Techno-logical 40%	Installed capacity	0.05	5	3	2	1	2	1
	Capacity factor	0.05	4	3	3	1	5	5
	Nominal resource	0.05	4	4	3	2	3	2
	TRL	0.2	5	4	3	3	3	3
	Required area	0.05	3	5	1	3	4	3
Applica-bility 30%	Impacted sites	0.1	5	5	1	1	3	2
	Site applicability	0.1	5	5	2	1	4	5
	Energy requirement	0.1	5	3	1	1	3	5
TOTAL		**1**	**4.2**	**4.0**	**2.4**	**2.0**	**3.6**	**3.4**

WO=Wind Offshore, FS=Floating Solar, WE=Wave Energy, TE=Tidal Energy, OTEC, SG=Salinity Gradient

Impacted sites

Refers to the number of potential sites that could be found where the technology implementation could be feasible.

Site applicability

This criterion includes the identification of the applicability of the technology in the sites of interest, giving a higher score to the technologies that can be implemented in more sites within the evaluation scenario.

Energy requirement

This criterion evaluates the capacity to cover the requirements of the particular energy demands of the analyzed sites.

B. Priorization results

The results account for the capabilities of each technology to generate the energy under each site conditions. The qualitative categorization of the factors of interest is used with a value of 5 for the rating "Very favorable", 4 for "Favorable", 3 for "Medium", 2 for "Unfavorable" and 1 for "Very unfavorable". Table VII shows the evaluation matrix. The weights presented are set based on the evaluation preferences. In this case, greater relevance is given to the technological component (40%) with respect to the site, resource and applicability components. Ultimately, these weights can be assigned based on a project's criteria.

The final score points out wind offshore and floating solar as the highest-ranking technologies in level 4, then OTEC and salinity gradient in level 3, and at the end wave and tidal energy in level 2, in the scale from 1 to 5.

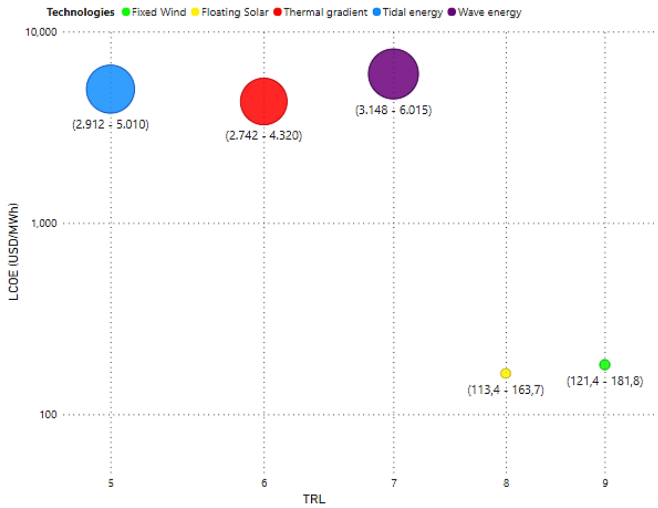

Fig. 1. LCOE for the technologies in the same location.

V. COSTS ANALYSIS

We calculated the levelized cost of energy (LCOE) production taking into account the ranges of capacity factors determined for each technology, the installed capacities defined from the state of the art of the implementation of these offshore technologies worldwide, and additionally the depths and distances to the coast considered in each scenario.

In Fig. 1 we observe a comparative graph for one of the best locations of the evaluation scenario (8 km to the coast and 44 m depth), with the LCOE for each technology (except salinity gradient which cannot be evaluated in all the locations), in order to identify the technology that would show the lowest LCOE for that specific site (floating solar in this case).

It can be seen that the technology with the lowest LCOE after floating solar is fixed offshore wind, as can be expected because it is the most developed of all (highest TRL), and it should be noted that the costs of floating solar technology that are presented in the graph are based on projects installed in artificial bodies of water or lakes. Therefore, as projects installed in the real conditions of the open sea become available as a reference, the costs may vary and there will be another perspective of the production costs of floating solar technology, which means that offshore wind with fixed foundations can be assumed as the best LCOE case.

VI. CONCLUSION

Offshore wind and floating solar have advantages over the other technologies. In the case of offshore wind, it can be considered well-proven so far and the one with the highest commercial success, while the main challenges are found on site, like high depths that determine important foundation requirements, high variability that may be observed in some locations and also the area required for generation. Floating solar technology is preceded by the successful implementation of its ground version, but faces challenges regarding the resource variability, and it is one step below offshore wind due to technological aspects, such as the installed capacity of these projects and the capacity factor.

An interesting finding has to do with the performance of OTEC and salinity gradient technologies. Although their TRL is not the highest of the evaluation scenario, the applicability and availability of the resource based on the current technological development show their high potential in the country.

On the other hand, the current technological status of the conversion devices of wave and tidal energy, for the conditions of the resource in the Colombian Caribbean, shows that their implementation will depend on their future development, therefore, technological monitoring is recommended.

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