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Evaluation of Solar and Wind Power Potential in Barranquilla, Colombia

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***Abstract*—This study evaluates the feasibility of solar and wind energy systems in Barranquilla, Colombia. It compares two solar technologies (Polycrystalline and Thin Film) and wind power, analyzing their design, technology, and potential energy outputs. Meteorological data was collected to support the analysis. The project aims to identify cost-efficient renewable energy solutions. Results demonstrate the potential for both solar and wind energy in Barranquilla, with detailed economic, environmental, and technical comparisons. The study concludes by recommending the most suitable technology for the region based on efficiency, environmental impact, and cost.**

***Keywords*—**Renewable energy, Solar power, Wind energy, Energy efficiency, Economic analysis of renewable energy

I. INTRODUCTION

This is the project to evaluate the feasibility of a solar or wind energy system for a client in Nouadhibou, Mauritania or Barranquilla, Colombia. This project will focus on Barranquilla, Colombia, since the data shows bigger potential for renewable energy investment and the actual energy demand is higher.

Renewable energy is considered here the A.) PV or B.) CSP or C.) Wind or D.) Bioenergy. Therefore, we propose two solutions with PV power, by polycrystalline and thin film, and Wind power in certain areas.

Locations close to the client's facilities have been pre-selected which will be introduced in the coming sector, and a whole year's hourly meteorological data has been collected for our project. For each of the designed power plants, the adopted technology and module will be well-evaluated before data analysis and provide a number of configurations and layouts for the clients to support their decision and to make the process.

The main goal of the project is to exploit various renewable technologies in certain areas and come up with a cost-efficient analysis to support the project. At the end of the report, we will conclude the pros and cons of comparing these two power plants with multiple dimensions and illustrate our result with further discussion.

II. SOLAR PV

This Chapter involves the two technologies of solar power. We estimate the Polycrystalline and Thin Film. The method of the analysis includes the relevant device selection, storage needs, and economic analysis. Moreover, we will look into the pros and cons and the technological issues, as well as the environmental effects.

The calculation is made by Excel and the result will be shown in the table. Eventually, in chapter 4, we will conclude the result and proceed with the discussion.

A. PV Array Comparison

1) Data and Analysis

The system is designed on Standard Testing Condition (STC) with a goal of 100MW. The calculation is strongly relevant to the chosen devices, which are PV modules, Thin Film modules and the module of the inverter. The following Table.1 shows the key parameters for the analysis in the selected PV and Thin Film module.

TABLE I. Datasheet of the module and key parameters

Datasheet	Polycrystalline	Thin Film
PV modules	FU 285P	First Polar series 6 - FS6450
Max Power	285	450
Voc	39.1	221.1
Isc	9.25	2.57
Vmpp	32.1	186.8
Impp	8.9	2.41
Efficiency	17.45%	18.20%

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Table 2 illustrates the key parameters of the chosen Central inverter, which will be related to the scale of a power array.

TABLE II. Datasheet of the Inverter module and key parameters

Datasheet	Central Inverter For PV	Central Inverter for Thin Film
Inverter modules	SMA Sunny Central 3000-EV	SMA Sunny Central 3001-EV
Efficiency	98.80%	98.80%
Vmax DC input	1500	1500
Vmpp min DC input	956	956
Vmpp max DC input	1425	1425
Imax DC input	3200	3200

Table 3 provides the number of required panels from the calculation with PV and Thin Film technology. In the meanwhile, the DC/AC ratio is decided as 1.2, which will be defined in the upcoming section.

TABLE III. In array maximum numbers of panels and calculation

Array	Polycrystalline	Thin Film
Modules in series	30	6
Module in parallel String	345	1245
Number of Arrays	43	38
Modules in an Array	10350	7470
Vmpp	963	1120.8
Impp	3070.5	3000.45
DC Power/ Array	2956891.5	3362904.36
Ratio DC/AC	1.2	1.2

1) System Design and Sizing

In this section, before the layout configuration, the calculation should include all possibilities of losses and effects. The shading effect is an essential issue for solar energy. The percentage of it is assumed as 0.95 because this value is commonly used in a standard reality condition of the dry season. Moreover, in certain areas, the weather is usually hot and dry in a year.

TABLE IV. In power plant's final calculation

Plant	Polycrystalline	Thin Film
Total number of modules	445050	283860
DC Power(W)	126839250	127737000
Number of Arrays	43	38
shading effect	0.95	0.95
DC shading effects (W)	120497287.5	121350150
AC Power(MW)	100.41	101.13
Investment costs (USD/WDC)	1	0.8
Total investment costs (MUSD)	120.50	97.08

1) Layout Configuration

Table 5 provides the areas of a single panel from two different technologies, which lets us calculate the total required areas for each power plant.

In the layout configuration, the blue areas are designed to settle the solar panels, and the distance between the panels is shown as yellow areas. The distance is defined as ½ of the width of the panels.

In the designed area, as per the provided data from the website, the best tilt angle of the PV panel in Barranquilla is 14° [1].

TABLE V. Datasheet of the PV panels and Thin film's size

s	Polycrystalline	Thin Film
Length	1.567	2.009
Width	0.95	1.232
Area	1.49	2.47

TABLE VI. Total required area for each power plant

Total	Polycrystalline	Thin Film
Numbers	445050	321210
Area (m2)	662523.68	702578.48
Total	Polycrystalline	Thin Film

Fig. 1. Layout configuration of solar PV

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B. Selection of Technology and DC-AC

To design a large-scale power plant, the selection of solar collectors, converters, and storage systems is the first thing to determine. In the project, we chose "FuturaSun FU 285 P" as the collector for the polycrystalline photovoltaic base system and "First Solar Series 6 FS-6450" as the collector for the thin film base system. Both of the collectors we decided on having the largest maximum power at the standard test condition compared with other modules in the same series, due to their highest efficiency and power output. Therefore, the system we designed would have better performance but occupy less land area.

The inverter used in both systems is "Sunny Central 3000-EV" which has almost 100% efficiency. Even though the central inverter cannot adapt every panel to the highest power output, it took less land area and easier to control. With the larger limited value of inverter voltage and current, the systems are able to contain more modules in an array. The calculation procedures for the designed arrays are listed in the previous section. One of the decisive factors for power generated is the DC-to-AC ratio. The way to obtain the accurate DC-to-AC ratio is to record the DC electricity generated and AC electricity output throughout the year and do the analysis. In this case, it is difficult to calculate the exact value of the ratio. Therefore, we assumed the ratio to be 1.2 since the inverter ratio for utility-scale power plants would be larger than the average value which is 1.15 [2].

C. PV Storage

The systems requested 8-hour storage, which the storage capacity needed to be considered based on the daily electricity generated. Since solar energy is intermittent, less than half a year, the daily energy output reaches 800MWh. Therefore, for solar systems, it's unable to select a storage system with 800 MWh capacity. The designed storage capacity would be calculated based on different criteria.

As shown in table A1 in Appendix, there are four kinds of designed conditions. The first two are to store energy exceeding the annual average value, the others are to store above the third quartile value. Then divide each of them into two groups which are setting the upper limits for the storage capacity as the average and third quartile capable storage capacities.

Blue lines in figure A3a and b in Appendix are the daily storage after sending an amount of electricity to grids. To not oversizing and waste the storage capacity, the orange areas in the two figures are the third quartile values of the annually available storage capacities. The overlapping area of the blue and orange area is the final total energy stored throughout the year.

The maximum annual available electricity of the PV base system appears when storage capacity is set as the third quartile value of the annual available storage capacity. The electricity demand during the night time is larger than during the day time. Therefore, for both PV base and thin-film base systems, the designed conditions for the storage system will follow the second set, which is sending electricity below the average value of total generation into grids and storing energy below the third quartile value of total storage. The concept of energy distribution throughout the year is shown in Figure 2.

The chosen storage capacity for PV and thin film base power plants are 501 and 453 MWh. The storage system suitable for those amounts of capacities and properties is the Compressed Air Energy Storage (CAES).

TABLE VII. The comparison between storage systems in PV and thin film base power plants

AVG--Q3	PV	Thin Film
storage capacity for a day (MWh)	453.00	501.04
annual storage (GWh)	114.58	126.72
annual electricity connect to grids (GWh)	84.01	92.92
annual energy wasted (GWh)	5.525	6.11
annual available electricity (GWh)	198.59	219.64
annual energy wasted (%)	2.70%	2.70%
annual available electricity (%)	97.30%	97.30%

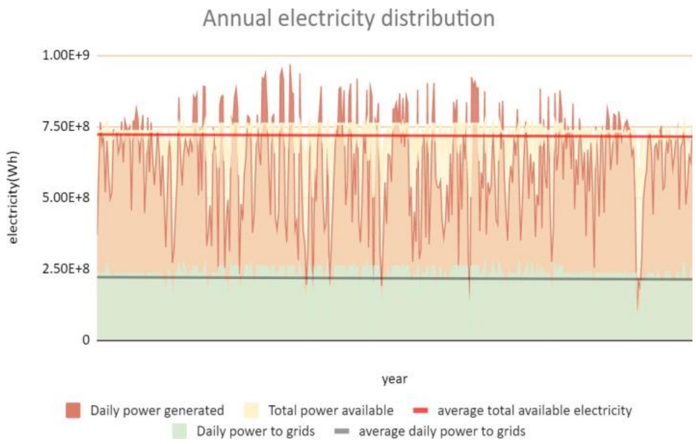

Fig. 2. Annual electricity distribution of thin film base power plant.

D. Economic Analysis

For a utility-scale solar power plant, the investment cost includes the module price, inverter price, installation, construction, testing, commissioning cost, and so on. The average PV module costs 0.47 USD/Wdc and the inverter costs about 0.04 to 0.05USD/Wdc. The structural components and transmission line cost about 0.1 to 0.21 USD/Wdc and 0.02 USD/Wdc. The services such as testing, interconnection, commissioning cost range between 0.03 to 0.09 USD/Wdc [2]. Therefore, the assumed total investment cost for PV and thin-film base power plants given from the project description, 1 and 0.8 USD/Wdc, are covering all costs required. The total investment cost would be the investment cost per energy density multiplied by the designed power plant DC capacity.

The operation and maintenance cost per year in 2020 is predicted as 6.8326 USD/kW-yr following the trend in figure A4 in Appendix[1]. As the cost will not decrease without limitation, it's assumed the lowest cost is the same as the cost in 2020.

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Considering investment cost and other expenses, the payback years for PV and thin-film power plants with storage systems are 40 and 32 years, respectively. Without the storage systems, the expenses can be recovered within 25 and 18 years. However, as mentioned, the energy demand during the nighttime is higher than the daytime which doesn't match the energy supply profile. Therefore, the storage systems for solar power plants in this project are necessary.

TABLE VIII. Economic breakdown of PV and thin-film power plants with storage systems.

	PV	Thin Film
Total investment costs (MUSD)	120.50	97.08
Annual maintenance cost (MUSD/yr)	0.82	0.83
Annual power output (GWh)	204.11	225.75
CAES storage capital cost (MUSD)	74.73	78.29
CAES annual maintenance cost (MUSD/yr)	0.000359	0.000376
Annual power stored (GWh)	114.58	126.73
Price purchased by government (USD/kWh)	0.0277	0.0277
Annual selling price(MUSD/yr)	5.65	6.25
Pay back (year)	40.42	32.33

TABLE IX. Economic breakdown of PV and thin film power plants without storage systems.

	PV	Thin Film
Total investment costs (MUSD)	120.50	97.08
Annual maintenance cost (MUSD/yr)	0.82	0.83
Annual power output (GWh)	204.11	225.75
Price purchased by government (USD/kWh)	0.0277	0.0277
Annual selling price(MUSD/yr)	5.65	6.25
Pay back (year)	24.95	17.90

E. Advantages and disadvantages

From the calculated results and datasheets of the PV and thin-film module, it is able to analyze the difference between the two technologies. Table 10 summarizes the advantages and disadvantages of each technology.

The module efficiency and the IV-curve fill factor for the two chosen modules are similar which makes them easier to compare. The thin-film power plant has higher economic benefits which generate more power and needs a shorter period to pay back, compared with the PV power plant. However, due to the toxic components and non-easy recycle property, the final choice for the solar project will be the PV power plant.

TABLE X. The Pros and Cons of different solar technologies.

	Polycrystalline	Thin film
Adv	1. less land space required 2. firm panel structure 3. smaller size for storage system 4. lower clipping energy 5. more environmental friendly material	1. lower payback period 2. higher module efficiency 3. lower investment cost 4. larger annual power generation 5. larger storage capacity
Disadv	1. higher temperature impact 2. lower module efficiency 3. higher investment cost 4. lower annual power generation 5. less flexibility	1. larger land space required 2. higher toxicity 3. higher clipping energy 4. labor cost for special clips for mounting 5. require more circuit combiners and fuses

F. Environmental and technical issues

The impacts of large scale solar projects include environmental and technical concerns which are listed below:

Environmental:

1. The manufacturing process of solar panels would use hazardous material to clean and purify the semiconductor surface which generates pollution and causes environmental or public health threats.
2. The thin film has more toxic material than PV. For both solar technologies, if the panel did not recycle or deposit properly, it would spoil the land and environment.
3. To produce a high-efficiency panel, it requires a huge amount of energy and heat for processing. Most of the energy supplies are traditional fuels which increase the carbon emission throughout the lifecycle of the panel.

Technical:

1. The hot spot is one of the most common issues of solar systems. The dust or not well connection would make the panel too warm. Those irreversible damages would reduce the panel efficiency and lifetime.
2. The moisture would cause panel corrosion if the panel has cracks or is not laminated properly. The location chosen for the power plant is close to the sea which would increase the possibility of corrosion happening.
3. The corrosion and oxidation of the wiring would affect the panel performance and even the operation safety. Also, the lifetime of the inverter is usually less than the solar module. The inverter needs to be repaired within 10 to 15 years or it would reduce the power plant performance.

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III. WIND TURBINES

In this chapter, a wind farm with a storage system is proposed in Barranquilla, Colombia. The turbine selection and wind farm layout are based on the provided wind data. According to the power generated in the wind condition, an 8-hour storage system is also designed and integrated into the system. Finally, the economic analysis of the system along with some technical challenges and environmental issues are raised at the end of this chapter. With the proposal of a wind farm and storage system, the feasibility of a solar PV system and wind farm can be compared in the following chapters.

A. Wind Data Analysis

The provided wind data does not indicate the height of wind speed, therefore, it is assumed that it is measured 10 m above sea level as common wind speed data. In order to analyze the wind speed at higher sea level, the wind profile is proceeded with the formula (1) to consider the effect of wind shear. The wind speed in a certain height z is calculated with the roughness length Z0. The initial height is selected as 100 m above sea level, and the roughness length of Barranquilla is chosen as 0.8 since it is a large city with 2.3 million people and many large residential buildings [3][4]. The wind distribution at 100 m is shown in Figure 3, around 24.8% of the wind is lower than 3 m/s, and the average wind speed is 7.15 m/s.

$$V(z) = V_{ref} \frac{\ln \frac{z}{Z_0}}{\ln \frac{z_{ref}}{Z_0}}$$

(1) [3]

α + β = χ.

(1) (1)

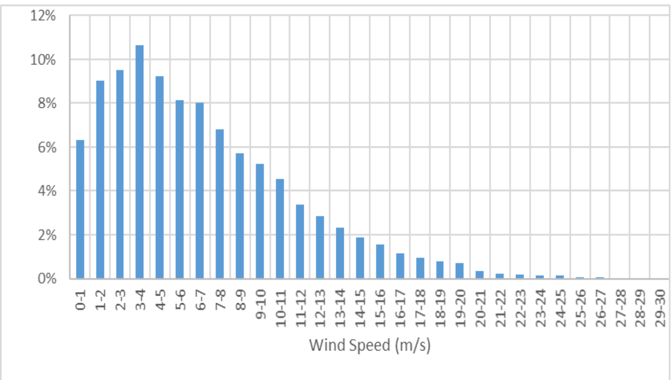

Fig. 3. Wind speed distribution at 100 m.

The wind direction and wind speed are analyzed in Figure 4. The result shows that about 55% of wind comes from the east, 19.4% from the northeast and 20% from the southeast. It is quite consistent that the wind in Barranquilla is coming from the east, therefore the wind farm should be heading east in the layout.

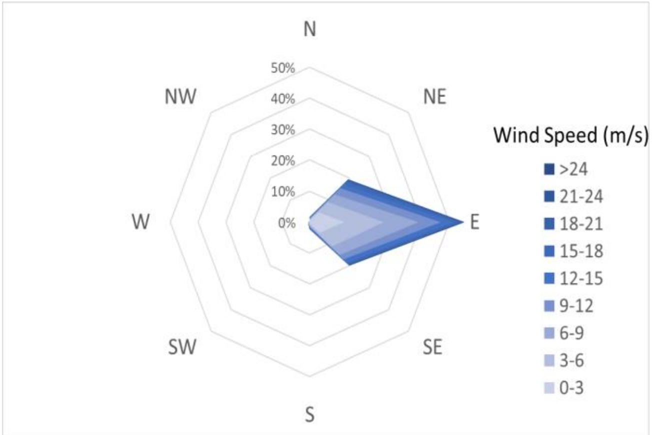

Fig. 4. Rose diagram of wind at 100 m.

The hourly average wind speed patent in a day is also analyzed in Appendix Figure A5. The result shows that the wind speed is usually higher from 10 AM to 8 PM, and consistent throughout different seasons. Also, Table 11 shows the wind speed from December to February is higher than the yearly average, and from September to November, the wind speed is lower than the yearly average. It indicates that there is a seasonal difference in the wind condition, which will affect power generation in different months.

TABLE XI. Seasonal and Yearly average wind speed

	Dec - Feb	Mar-May	Jun - Aug	Sep - Nov	Yearly
Average Wind Speed (m/s)	9.26	8.9	5.71	4.87	7.15

B. Wind Farm Layout

By analyzing the wind condition in the previous section, the yearly average wind speed is
7.15 m/s at 100 m above sea level. According to IEC wind turbine classification [5], the wind turbines are divided into 3 classes, and Table A3 in Appendix A shows the classification detail. From the wind turbine classification, type IIIa turbines are selected in this project. Three commercially available IIIa turbines are compared in Table 12 and Figure A5 in Appendix A. Table 12 shows some basic parameters of each turbine, and Figure A5 shows their power curve. Since the SWT-3.15 has the highest power output at wind speed below 9 m/s, and the wind condition in Barranquilla is usually below this speed, therefore SWT-3.15 is chosen for the designed wind farm.

TABLE XII. Parameters of potential wind turbines [5]

	Vestas V126-3.3	General Electric GE 3.4-137	Siemens SWT-3.15-142
Rated power (kW)	3300	3400	3150
Cut-in wind speed (m/s)	3	3	3
Rated wind speed (m/s)	12	12	11
Cut-out wind speed (m/s)	22.5	25	22.5
Rotor diameter (m)	126	137	142
Maximum hub-height (m)	137	155	165

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Since the wind condition at 100 m above sea level can rarely reach the rated power of SWT-3.15 turbine, the highest available hub height of SWT-3.15 is chosen as 165 m. The wind shear is considered again by formula (1), and the annual average wind speed is obtained as 7.9 m/s. Figure 5 shows the annual power output during the day, and the average power output of a single turbine is 2079 kW.

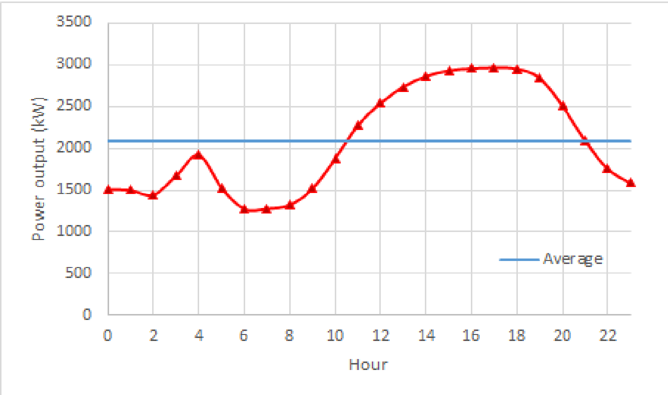

Fig. 5. Annual average output power during a day

Designing a wind farm layout with optimal efficiency and minimizing the wake effect is essential to a wind power project. Many different studies are indicating that the distance between turbines should be around 5 times to 7 times (5 D ~ 7 D) the rotor diameter [6] [7]. Also, another study suggested that the optimal layout should depend on the wind model in different sites. [8] The distance between turbines is chosen to be 7 D at the most common wind direction which is at the east-west direction and 5 D at the north-south direction. By considering the wake loss of 5% and transmission loss of 10% [8] the total turbine needed would be 100 MW divided by the average power output (2079 kW) in a year and 0.95 and 0.9 for the losses. The result shows 57 turbines are needed, and the required area is 23.94 km2 shown in Figure 6.

Fig. 6. The layout of the potential wind farm

C. Wind Energy Storage

The project requires selecting a storage system lasting for 8 hours which indicates that the energy of 800MWh needs to be provided to the grid. According to the Ragone chart, the feasible options are Pumped Hydro Energy Storage (PHES), Compressed Air Energy Storage (CAES), and Liquid Air Energy Storage (LAES), Owing to the topographical constraints and safety concerns PHES and LAES were eliminated and the team decided to propose a CAES plant. The proximity of Barranquilla to the seashore clears the air for the necessity of salt caverns for CAES. Additionally, a lifetime of 30 years is an added advantage for CAES.

A CAES plant, with an estimated efficiency of 74%, of 150.1501 MW (also considering transmission losses and other misc losses to be around 10%) requires a land of 1 acre [9][10].

D. Economic Analysis

The following Table 13 to Table 15 shows the economic calculation on the installation cost per kW of energy and the energy cost per kWh for the system.

TABLE XIII. Wind Plant Parameters

S.No	Parameter	Value
1	Capital cost	1800$/kW
2	O&M cost	9$/MWh
3	Rated power (P_rated)	2.079 MW
4	Number of turbines (n)	57
5	Land required (L_w)	23.94 sq km
6	Selling price of wind power (SP_w)	0.027$/kWh
7	Average Land cost in Colombia	1618.74$/acre

TABLE XIV. CAES Plant Parameters

S.No	Parameter	Value
1	Capital cost	1250$/kW
2	O&M cost	6$/MW
3	Efficiency	74%
4	Lifetime	30 years
5	Power_to be supplied to grid (P_g)	100MW
6	Transmission & other losses	10%
7	Power-_to be stored (P_s)	150.15MW
9	Energy_to be supplied to grid	800MWh
10	Energy_to be stored (E_s)	1201.20MWh
11	Land required (L_s)	1 acre
12	Average Land cost in Colombia	1618.744$/acre

TABLE XV. Economic Breakdown

S.No	Type of Cost	With Storage	Without Storage
1	Capital Costs	400.99 M$	213.30 M$
2	O&M Costs	10.24 M$	9.34 M$
3	Land Costs	9.57 M$	9.57 M$
4	Investment	410.57 M$	222.88 M$
5	Yearly Income	17.78 M$	18.68M$

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The Break-Even period would be approximately 23 years for the Wind plant including storage whereas only 12 years for only wind plants. [10-20].All the calculations w.r.t economic breakdown are done with reference to Appendix B.

E. Technical Challenges and Environmental Concerns

The technical challenges and environmental concerns in the wind farm of this project are listed below.

Technical:

1. During the expansion of air during the CAES storage process, the underground chamber will lead to an uneven generation of electricity which could lead to a rise in expenses.

2. If the wind farm is designed to meet the demand during the low-wind season, there will be a surplus of wind energy on most of the days in a year. However, if the average wind condition is considered, there will be a shortage of energy in the low-wind season.

3.There is a large wetland area at the east of Barranquilla, the stability of land should be considered while building a wind farm.

Environmental:

1.Wind turbine blades create a lot of noise which could have a negative impact on the surroundings.

2.Given the fact that Barranquilla is sandwiched between seashore and protected areas, land acquisition for the wind or CAES plants would be difficult.

3.There is a large protected area called "Large Marsh of Saint Martha" at the southeast of the proposed wind farm. The mangrove ecosystem of the marsh consists of a high diversity of birds and animals, which should be a concern in this project [21].

IV. RESULT AND DISCUSSION

The results of the economic comparison of the polycrystalline PV and wind energy systems are shown in Table 16, indicating that the investment cost of a wind farm with storage is higher than the solar with the storage system. The payback-year analysis shows the wind farm has a shorter payback period, this may be because the total energy sold in wind farms is overestimated at this stage of the project. It is assumed that all of the energy generated is sold even if the generation is greater than the demand. Also, solar PV modules have a longer lifetime than wind turbines. The lifetime of a wind turbine is about 20 years which is less than the payback year. In the economic aspect, solar PV with storage systems is more recommended in Barranquilla.

The wetland and marsh ecosystem close to Barranquilla are precious natural resources. The solar PV system uses less land area compared to wind farms and has less effect on the wild birds in the area. Overall, a solar PV system would be a better choice in terms of the environment as well.

In terms of technical issues, the solar panels are placed on the ground. It would be easier to maintain than wind turbines. Also, there is a seasonal wind speed difference in Barranquilla, which leads to energy supply not able to meet the demand in many months and increases the instability of wind energy. Therefore, based on the economic, environmental, and technical considerations, the final choice for the renewable power plant is the solar PV system in Barranquilla.

	PV+Storage	Wind+Storage
Annual power output (GWh)	204.11	895.25
Total Investment (M$)	195.23	410.57
Annual O&M Cost(M$)	0.82	10.24
Annual Income (M$)	5.65	13.93
Total land needed (km2)	0.66	23.94
Energy cost ($/kWh)	0.032	0.027
Payback years	40.3	22.8

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