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Comparison of Residential Wind and Solar Energy Generation in the Island of Puerto Rico

Rachid Darbali-Zamora, Carlos J. Gómez-Méndez and Dr. Andrés J. Díaz-Castillo

Department of Electrical and Computer Engineering
University of Puerto Rico
Mayagüez 00681-9000
E-mail: rachid.darbali@upr.edu, carlos.gomez@upr.edu, andres.diaz@ece.uprm.edu

Abstract. In order to meet growing energy demands, the dependency on crude oil, coal and natural gas has increased in an effort to supply the world's energy needs. This has created the need for using alternative energy sources for generating electricity. In Puerto Rico, there is a growing interest in renewable energy, particularly solar energy and wind energy. Renewable energy sources are a variable source of energy due to their dependency on natural resources. For this reason it is necessary to determine the feasibility of these projects. Wind speed and solar radiation data from CariCOOS, NOAA, the NRCS, the NSRDB and the LTER are analyzed in order to estimate yearly solar and wind energy generation on the island. Using this yearly estimate, an economic comparison between residential scale wind and solar projects is presented.

Index Terms – solar energy, wind energy, wind turbines, solar panels, feasibility, economic analysis

1. Introduction

The increasing global energy demand is mostly met from burning fossil fuels. The rate at which these fuels are being consumed is higher than the rate at which they are formed (generally millions of years). In order to decrease the rate of consumption of fossil fuels and to prevent them from being completely depleted, renewable, sustainable and economically viable energy sources are needed as alternatives. Burning fossil fuels also releases carbon dioxide (CO_2) and other harmful green house gases into the environment, causing global climate changes. Renewable energy sources can help reduce these CO_2 emissions. Despite the popularity of renewable energy, in Puerto Rico ninety-nine percent (99%) of the total energy produced is still fossil-fuel based [1]. In the US close to eighty-two (82%) is attributed to fossil fuels. Wind power and solar power are a clean, renewable and readily available forms of energy derived from the wind and sunlight, respectively.

In order to extract energy from these natural sources, wind turbines and photovoltaic panels (PV) are employed. These wind turbines use blades connected to an electric generator shaft that rotates once the blades are hit by strong winds. Once the shaft is in motion, the electric generator spins and converts the wind's kinetic energy into mechanical energy used to produce electricity. PV systems are used to absorb sunlight and directly convert this solar energy into electricity to power homes and businesses. These technologies can be employed in Puerto Rico, but it is important to assure their locations are feasible. Locations towards the west of Puerto Rico prove to have promising wind speeds for wind turbine projects. For solar energy, Puerto Rico's geographic nature enables a generous amount of solar resources [2]. As of 2010 Puerto Rico's renewable generation was less than one percent (1%) and for 2015 is estimated to reach five percent (5%) [3]. In the US, renewable energy has already reached thirteen percent (13%). In the following sections, wind and solar resources are used to determine available wind and solar energy in different locations of Puerto Rico. These results are analyzed in order to determine wind and solar project feasibility.

This article is organized in the following manner: section 2 presents the available wind and solar energy resources for selected sites in Puerto Rico. Available solar radiation data is presented and analyzed. Section 3 illustrates the estimated amount of wind and solar energy generated at each site. A comparison of these results is shown in section 4. In section 5, the Net Present Value (NPV) is used to analyze the economic viability of wind and solar projects, in the north, south, west and east of Puerto Rico. Finally, the conclusion is presented in section 6.

2. Wind and Solar Resources in Puerto Rico

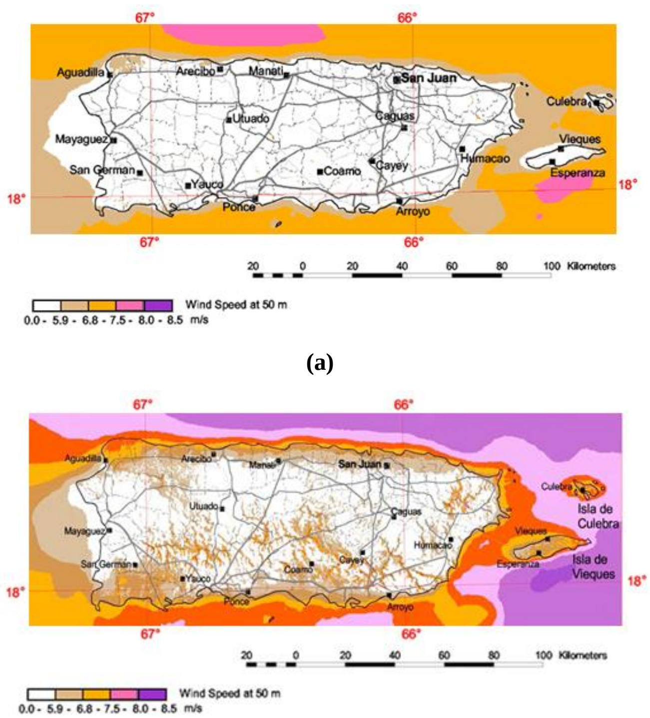
Puerto Rico is a mountainous island in the Caribbean with a total area of 9,104km^2 and a population of approximately 3,548,397 [U.S. Census Bureau, 2014]. Electricity is mainly generated through fossil fuels; however, renewable sources such as hydroelectric, solar, wind, waste-to-energy are also used [4]. Wind speed data from Puerto Rico is gathered from CariCOOS and NOAA. These stations are located in different coasts of Puerto Rico. Solar resource data is obtained from the NSRDB. This data is gathered from the five major airports in Puerto Rico. Solar radiation data is also obtained from the NRCS and from the LTER program.

A. Wind Resources In Puerto Rico

Wind speed, caused by changes in air pressure, is the rate of distance that air travels per unit of time. Wind speed is affected by its surrounding terrain. Given Puerto Rico's geography, favorable winds can be found towards the coast of the island. In order to identify which locations have favorable wind characteristics, hourly wind speed data was obtained from CariCOOS. All studied sites are located near the coasts of the following municipalities: Aguadilla, Cabo Rojo, Salinas, Yabucoa, Fajardo, and San Juan. Wind speed data is also provided by NOAA for the locations of Mayagüez and Arecibo. Table I illustrates the wind measurement sites descriptions as well as the average wind speeds at an adjusted height of 18m. Figure 1 illustrates the NREL and DOE wind speed maps used for comparison.

TABLE I: Wind Measurement Site Description

Agency	Location	Lat.	Long.	Average Wind Speed (m/s)
CariCOOS	*Aguadilla*	18.43	-67.16	*3.1*
	San Juan	18.46	-66.13	*4.4*
	Salinas	17.93	-66.16	*5.3*
	Cabo Rojo	18.10	-67.19	*2.1*
	Yabucoa	18.05	-65.83	*4.1*
	Fajardo	18.29	-65.63	*4.2*
NOAA	*Mayagüez*	18.22	-67.16	*2.7*
	Arecibo	18.48	-66.70	*3.6*



(a)

(b)

Fig. 1: NREL and DOE wind speed map of Puerto Rico. (a) Wind speed maps at a height of 50 meters. (b)Wind speed maps at a height of 70 meters.

Winds in the island range from 0m/s to 5.9m/s. They travel from the northeast towards the southwest of the island. Puerto Rico is subject to three different kinds of winds: sea breezes, land breezes and the trade winds that blow from the east towards the west throughout most of the year. Due to their proximity to the ocean, the winds of the selected sites are mainly produced by both trade winds and sea breezes. Average wind speeds from these studied locations show that the east of Puerto Rico is subject to strong winds, receiving trade winds directly. As locations move farther from the east, winds are slowed down by the island's mountainous topography. In Puerto Rico the best winds can be found in the northern, eastern and southern coasts of the island.

Figure 1 shows how wind speed measurements increase at higher heights. As the measurement increases from 50m to 70m, there is less drag force acting against the wind. In order to obtain energy generation for a specific wind turbine, the wind speed heights are adjusted in order to fit the wind turbines' specific hub height [5]. The logarithmic model for wind shear is shown in equation (1).

$$v_2/v_1 = ln(h_1/z_o)/ln(h_2/z_o) \quad (1)$$

This equation uses the relationship between height and wind speed, where v_2 is the wind speed at the desired height h_2, v_1 is the wind speed measured at a known height h_1, and z_o is the surface roughness length in meters. A simplified equation for wind speed interpolation can also be used [6]. This equation is known as the power law and is shown in equation (2).

$$v_2/v_1 = (h_2/h_1)^{\alpha} \quad (2)$$

The variable α in this equation is the wind shear coefficient. The wind shear coefficient varies with pressure, temperature and time of day. A commonly used value is one-seventh (1/7). Measuring wind speeds at two different heights makes it is possible to obtain the wind shear coefficient at any location. Solving for the wind shear coefficient in equation (2) will yield equation (3).

$$\alpha = ln(v_2/v_1)/ln(h_2/h_1) \quad (3)$$

For a more detailed interpolation, equation (4) can be used to obtain the wind shear exponent based on a location's terrain [7].

$$\alpha = 1/ln(z/z_o) \quad (4)$$

In this equation, the surface roughness is taken into account, measured at reference height z. Surface roughness length along with other wind speed parameters can be used to help build mathematical models for wind speed behavior prediction [8].

B. SOLAR RESOURCES IN PUERTO RICO

Solar radiation or irradiation is the instantaneous amount of solar energy received at a certain location, measured in *Wh/m^2* or in *Wh/m^2*. It can vary from $0W/m^2$ at night to around $1000W/m^2$ during peak hours. Solar insolation is the total amount of solar energy received at a particular location during a specified time period, for example *kWh/m^2-day*. It is the most commonly measured solar data. In other words, it is the instantaneous solar irradiance averaged over a given time period.

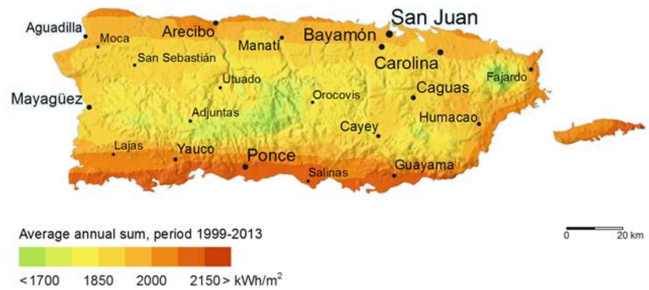
Due to Puerto Rico's tropical weather, solar energy is highly scattered. This is mainly due to atmospheric phenomena such as: clouds, water vapor and dust particles. Despite this, Puerto Rico's geographic location still provides generous solar resources that should be utilized to its maximum potential.

In order to determine the feasibility of solar projects, data from 14 different measurement stations has been obtained and analyzed. The NSRDB has a collection of Meteorological statistical (METSTAT) solar radiation data gathered from five major airports in Puerto Rico (Aguadilla, San Juan, Ponce, Mayagüez and Ceiba). Solar radiation data is also obtained from the NRCS. These sites are located towards the west of the island. Data for El Yunque rainforest in Rio Grade was obtained from the LTER program. The majority of the locations are from the west and southwest of Puerto Rico. These data is used in order to obtain the total solar radiation in each location. Table III illustrates the location description for the measurement sites as well as the obtained total solar radiation.

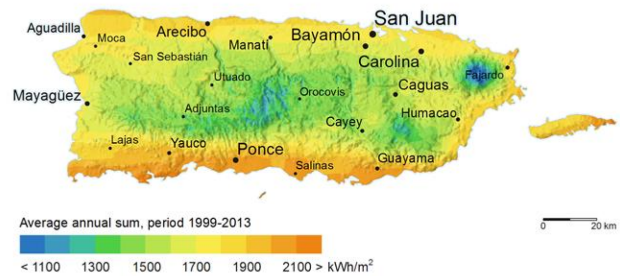
TABLE III: SOLAR MEASUREMENT SITE DESCRIPTION

Agency	Location	Lat.	Long.	Total Solar Radiation (kWh/m^2-yr)
NSRDB	*Aguadilla*	18.50	-67.13	2,031
	San Juan	18.43	-66.00	1,847
	Ponce	18.00	-66.55	1,974
	Mayagüez	18.25	-67.15	1,939
	Ceiba	18.25	-65.63	1,826
NRCS	*Guanica*	17.97	-66.87	1,722
	Cabo Rojo	17.98	-67.17	2,000
	Corozal	18.32	-66.03	1,617
	Juana Díaz	18.03	-66.53	1,879
	Adjuntas	18.15	-66.77	1,013
	Isabela	18.47	-67.04	1,866
	Mayagüez	18.21	-67.14	1,468
	Maricao	18.15	-67.00	1,181
LTER	*Rio Grande*	18.32	-65.82	784

These results are confirmed with average annual solar radiation maps generated by SolarGIS. Geographic information systems (GIS) are designed with the purpose of capturing and analyzing a variety of geographic data. This information can be later presented in the form of interactive maps. Figure 2 illustrates the SolarGIS radiation map used for comparison.



(a)



(b)

Fig. 2: SolarGIS solar radiation average annual sum. (a) Global Horizontal Irradiation in Puerto Rico. (b) Direct Normal Irradiation in Puerto Rico.

SolarGIS is a software tool designed for increasing efficiency in developing PV projects. These maps use satellite data collected from 1999 to 2012 in order to calculate solar radiation at multiple locations [9]. It provides solar maps for Global Horizontal Irradiation (GHI) and Direct Normal Irradiation (DNI). GHI is the total amount of solar radiation received at a plane parallel to the ground. It can be measured using a pyranometer sensor. On the other hand DNI is the rate of solar radiation arriving at the Earth's surface from the Sun's direct beam, on a plane perpendicular to that beam. In order to measure DNI, a pyrheliometer mounted on to a solar tracker is used. These SolarGIS maps are used to aid in validating the analyzed solar radiation data.

Results indicate that there is a strong correlation between the SolarGIS map from figure 2 and the total solar radiation analyzed from different locations. From these results, the most suitable locations for any type of solar system development lie in the south and in the extreme southwest of Puerto Rico. These locations are mostly dry and less susceptible to humidity. This is due to solar radiation and solar insolation both being strongly dependent on the weather conditions. Solar radiation decreases as locations get closer to the center of the island. This can be seen in the area of Mayagüez, where the NSRDB location which is farthest from the center of the island has more solar radiation than the NRCS locations which is closer to the center. In locations where there is significant amount of rainfall, there is lower solar radiation. Some of these locations are Rio Grande (El Yunque), Adjuntas, and Maricao [10].

3. Energy Generations in Puerto Rico

In order to compare the feasibility of wind and solar energy generation, wind and the solar systems are proposed, both rated at 6kW. These systems are used to calculate the available wind and solar resources.

A. *Wind Energy Generation In Puerto Rico*

For the wind power system, a single Bornay Inclin 6000 wind turbine is used [11]. Equation (5) illustrates the typical method used for calculating the energy generated by a wind turbine, using available wind speeds [12].

$$E_{WT} = \frac{1}{2} \times \rho \times v^3 \times A \times t \times n_{eff} \quad (5)$$

In this equation, ρ is air density in kg/m^3, v is wind speed in m/s, A is sweep area in m^2, t is time measured in hours and n_{eff} is the efficiency of the system. When the calculations are made, a 10% inaccuracy in wind speeds can produce a 33% miscalculation in actual power generation [13]. In order to effectively estimate wind energy generation, histograms have been generated for each site and paired with the selected wind turbine model. Table IV shows the annual wind energy calculated using an Inclin 6000 wind turbine.

TABLE IV: Annual Wind Energy Generated

Agency	Location	Energy Generated (kWh-yr)
CariCOOS	*Aguadilla*	*6,444*
	San Juan	*12,481*
	Salinas	*14,316*
	Cabo Rojo	*2,760*
	Yabucoa	*10,914*
	Fajardo	*11,284*
NOAA	*Arecibo*	*8,810*
	Mayagüez	*5,324*

Results show that the energy generated from wind varies from each location. This is caused by winds slowing down when traveling from east to the west of the island. The new locations of Arecibo and Mayagüez help demonstrate how wind energy generation decreases as winds approach the west of Puerto Rico. Figure 3 illustrates the annual energy generated using the Bornay Inclin 6000.

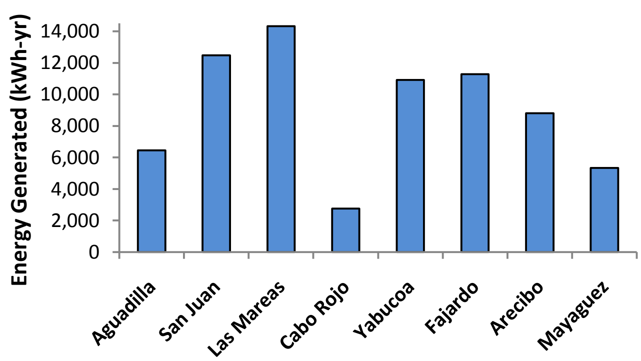


Fig. 3: Annual energy generated by wind power in selected locations around Puerto Rico.

B. *Solar Energy Generation In Puerto Rico*

In order to analyze the solar energy generation in each location, a 6kW grid tied solar power system is proposed. The system is composed of 24 solar panels, each with an efficiency of 15% and an area of 64.57” × 39.06”. Inverter efficiency is estimated to be 90% and the additional system losses are 5%. Equation (6) is used to calculate the energy generation of the proposed residential scale solar system [14].

$$E_{PV} = I_{solar} \times n_{PV} \times n_{eff} \times A_{PV} \quad (6)$$

In this equation, E_{PV} is the energy produced by the PV array in kWh and I_{solar} is the total solar radiation, measured in kWh/m^2. A_{PV} is the solar panel area measured in m^2. The variable η_{eff} includes the inverter efficiency and any additional system losses. Table V illustrates the annual energy calculated in each location.

TABLE V: Annual Solar Energy Generated

Agency	Location	Energy Generated (kWh-yr)
NSRDB	*Aguadilla*	11,700
	San Juan	10,638
	Ponce	11,372
	Mayaüez	11,171
	Ceiba	10,517
NRCS	*Guanica*	9,920
	Cabo Rojo	11,522
	Corozal	9,315
	Juana Diaz	10,824
	Adjuntas	5,833
	Isabela	10,750
	Mayagüez	8,457
	Maricao	6,802
LTER	*Rio Grande*	4,516

Each location proves to have sufficient energy generation for a residential scale solar energy project. Solar energy generation is more uniformed. Locations of Aguadilla, Ponce and Mayagüez proved to have largest energy generation. Figure 4 illustrates the annual energy generated using the proposed 6kW solar power system.

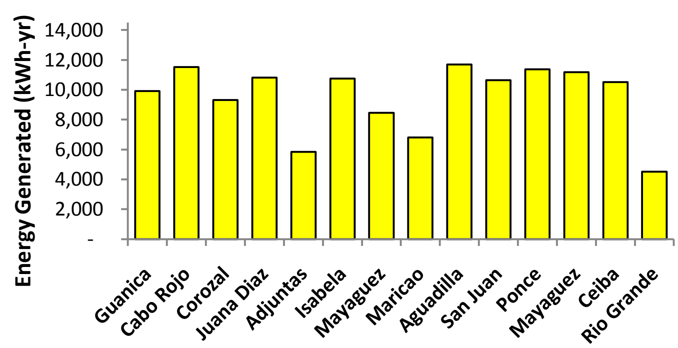


Fig. 4: Annual energy generated by solar power in selected locations around Puerto Rico.

4. Comparison of Solar and Wind Resources

Using the results obtained from analyzing wind and solar data, a comparison between energy generation for solar and wind resources is presented for the northern (San Juan), western (Mayagüez), southern (Juana Diaz and Salinas) and eastern (Ceiba and Fajardo) regions of Puerto Rico. For locations that do not share the same wind and solar measurement site, municipalities that prove to have the closest weather stations from one another were selected. Locations to the center are not considered due to lack of land for renewable energy projects. Another reason is that certain locations in the center of the island prove to have very poor wind resources. This is seen with the municipality of Gurabo, a location from CariCOOS that was discarded from the analysis due to its low wind speeds. Other locations were removed due to low solar resource. An example of this is the municipality of Rio Grande and Adjuntas, possessing low solar radiation due to excessive rainfall. Table VI shows an energy generation comparison between the north, west, south and east regions of Puerto Rico.

TABLE VI: COMPARISON OF ENERGY GENERATION

Direction	Location	Wind Energy (kWh)	Solar Energy (kWh)
North	*San Juan*	12,481	10,638
West	*Mayagüez*	5,324	11,171
South	*Juana Diaz*	-	10,824
	Salinas	14,316	-
East	*Ceiba*	-	10,517
	Fajardo	11,284	-

A comparison of the locations shows that the eastern region of Puerto Rico (Ceiba and Fajardo) possesses a balanced energy generation for residential scale solar and wind projects. Another location with prominent wind and solar generation is San Juan, located at the northern region of Puerto Rico. In the southern region of Puerto Rico, Juana Diaz is subject to strong wind and solar generation. The western region of the island proves to have insufficient wind generation due to lack of strong winds, while solar energy in this site is greater compared to other locations in the island. Figure 5 shows the graphed comparison of wind and solar energy generation between these locations.

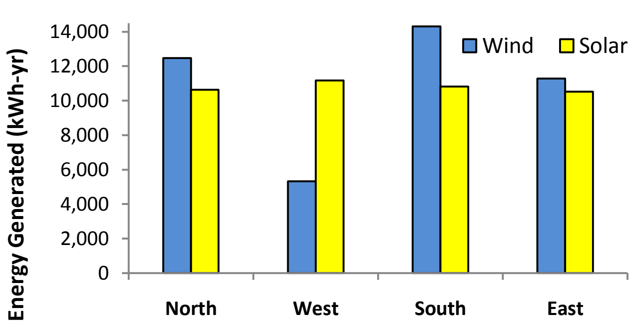


Fig. 5: Comparison of annual energy generated by wind and solar resources in different locations of Puerto Rico.

5. Economic Analysis

Although comparing wind and solar energy helps decide the best locations in terms of energy generation, an economic comparison involving the price of energy generated and the investment of the renewable energy system is performed in order to decide if the project is truly feasible. As of December 2013 the Puerto Rico Electric Power Authority (PREPA) supplies 1.3 million residential homes, generating on average 4,714kWh a yearly at a rate of 0.28 ¢/kWh [AEE, 2014]. For the proposed wind project, a single Inclin Bornay 6000 wind turbine is used. The cost of the system includes the wind turbine tower and additional mounting equipment. The proposed solar system is composed of 24 solar panels rated at 250W each. The projects are grid tied systems, directly connected to the electric distribution without the need of battery storage. In this scenario it is assumed that electric energy is either sold or purchased from the local utility company. The cost of the project takes into consideration the inverters as well as miscellaneous equipment. Table VII shows a summary of the solar and wind system capacity and utility details of the proposed project.

TABLE VII: PROJECT DESCRIPTION

General Case Scenario		
Capacity	6	kW
Project Lifetime	10	yrs
Electrical Retail Rate	13	¢/kWh
Utility Escalation	2	¢/kWh per year

There are significant differences between the initial investment of the projects as well as incentives available for each technology. The PV system has no moving parts and as a result requires minimal maintenance. A fixed operations and maintenance (O&M) cost of $0.01 per generated *kWh* is used for the wind turbine project. A cost of $21.00 per installed *kW* on a yearly basis is used for the O&M of PV system [NREL, 2013]. Table VIII shows a summary of the costs and incentives taken into consideration for the economic analysis.

TABLE VIII: PROJECT COSTS AND INCENTIVES

Project	***Bornay Inclin***	***ET Solar System***
Technology Cost	$ 15,000.00	$ 5,760.00
Equipment Cost	$ 22,600.00	$ 6,967.00
Installation Cost	$ 5,000.00	-
Total Cost	**$ 42,600.00**	**$12,727.00**
O&M		
Annual O&M	$ 143.16	$126.00
Annual Insurance	$ 170.00	$ 76.00
Inflation Rate	3%	3%
Financial Details		
Grant percentage	60%	40%
Grant 40%	$ 25,560.00	$ 5,090.80
Rate	10%	10%

The NPV analysis is performed on the selected locations towards the northern, western, southern and eastern regions of Puerto Rico. The equation that represents the NPV is shown in equation (7).

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+i)^n} \qquad (7)$$

In this equation, the variable n represents the cash flow period, while C_n is the cash flow and i is the rate of return. Figure 6 shows the graphed comparison of the NPV for wind and solar energy project.

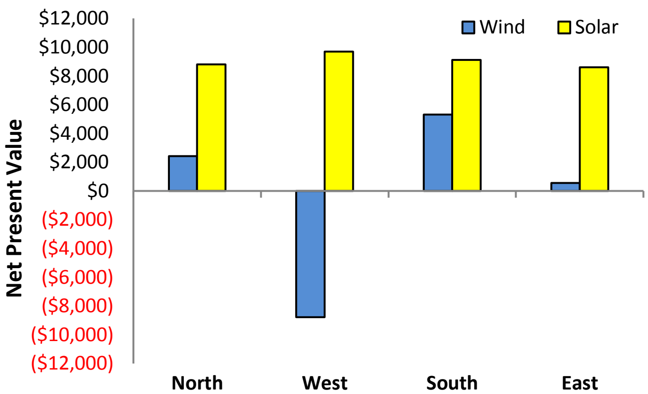


Fig. 6: Comparison of NPV for wind and solar resources in different locations of Puerto Rico.

Contrary to what is seen when comparing energy generation, wind energy does not prove to be a feasible investment at the moment. Although locations to the north and east have similar wind and solar energy generation, there is significant difference in NPV due to high initial cost for wind energy technology. From the analysis, solar energy proves to be the most prominent economic venture in these regions.

6. Conclusion

A comparison of wind and solar resources for renewable energy projects in the island of Puerto Rico is presented. In order to compare resources, available wind speed data is converted to energy by pairing it with a selected wind turbine power curve. Solar radiation is converted to energy using a solar panels area and efficiency. More emphasis is given on solar resources around the island. The price of this energy generated is used for the NPV analysis in order to determine the feasibility of each site. It is evident that there are significant wind and solar resources in the island of Puerto Rico. In terms of costs, solar energy is more feasible when compared to wind energy. Although prominent, wind energy has not reached the point where it can be considered as an affordable alternative in Puerto Rico. This project is the stepping stone for mathematical prediction models that can help forecast solar radiation trends for microgrid applications.

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