Feasibility Study of a Hybrid Solar and Wind Power System for an Island Community in The Bahamas

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Abstract – Renewable energy in The Bahamas holds promise as an alternative for electricity production, however, the country is heavily reliant on fossil fuels for electricity. This study examines the benefits of solar and wind energy on a community scale on the island of New Providence in The Bahamas and helps understand key factors that affect the implementation of hybrid renewable energy systems in an island community. The electricity usage of 500 homes (a mix of luxury and normal) is produced by a combined power generation system that includes rooftop photovoltaics and a wind turbine. The system is grid connected and assumes a net billing policy because of the lack of a net metering policy and incentives. For the study, an economic analysis along with sensitivity and risk analyses are performed to determine the system's feasibility and how its viability is affected by the uncertainty in its parameters. To perform the analysis, the RETScreen software suite is used. It is found that a combination of solar and wind for electricity generation is economically feasible in The Bahamas, even with the lack of incentives, where the net present value is within the range of US$14.0 million to US$25.1 million with a 95% confidence. Additionally, it is seen that current fuel costs and the initial cost of the system play key roles in the degree to which the system is feasible.

Keywords – Hybrid, Renewable, Energy, Bahamas, Solar, Wind

1. Introduction

The Caribbean lags behind North America and is often overlooked when it comes to development of renewable energy (RE) systems because of the high capital costs and lack of government policies to promote the use of RE [1]. Global demand for RE is mainly driven by concerns about the depletion of fossil fuel reserves, climate change, and increasing demand due to the growth of the world's population. Non-fossil fuel energy options are necessary in mitigating global warming, and can help reduce or eliminate greenhouse gas emissions [2].

The Caribbean as a whole has untapped sources of RE even though many of these countries have no discovered fossil fuel reserves. Many nations in the region use fossil fuels as their main source of energy with renewable resources accounting for less than 3% regionally [3]. These fuel imports deplete foreign exchange reserves and compound energy security issues [3]. The average cost of electricity in the Caribbean including fuel surcharge is US$ 0.31/kWh. This is particularly expensive compared to costs in the United States of America and Canada, which average US$ 0.12/kWh [4] and US$ 0.10/kWh [5], respectively. These high costs of electricity are predominantly caused by fuel import charges which are passed on to the consumer.

Aside from the potential economic benefits, sustainable energy can provide environmental benefits (e.g., improved air quality) and help in producing fresh water. A clean environment is particularly of interest to Caribbean countries as most heavily rely on tourism as their main source of income. Additionally, the use of RE resources reduces greenhouse gas emissions, thereby helping address a global environmental concern. On a local scale, the Caribbean with mostly low lying islands, is susceptible to destruction from global warming and the predicted associated rise in sea levels. It could submerge most of the Caribbean islands, including The Bahamas. In addition, RE technologies may improve tourism [6], which for many countries is the main economic industry.

There is a demand for the utilization of RE sources. However, one problem with RE sources is their unreliability. That is, they cannot provide a continuous power supply due to their intermittent nature [7] [8]. An integration of multiple sources into a hybrid RE system (HRES) can help mitigate this issue making them more reliable. HRESs are a topic of ongoing research where wind and solar radiation are widely favoured for their availability and their inexhaustibility [8]. They also have become viable alternatives for electrical power production and in remote areas are often the most-cost effective and reliable ways to produce power [9]. Usually before an HRES is implemented, a feasibility study is carried out [10].

Limited research has been conducted on RE in The Bahamas and the Caribbean in general. This lack of information is one of the factors that limits the development of the RE sector in this region. There are a few countries that have documented research along with successful implementation of RE. Of the countries that has been the focus of RE research, Mexico is a leader ein the region, ranking 27th worldwide in solar energy research contributions and 34th in wind energy research contributions [11]. Throughout the Caribbean only a few countries have already implemented renewable energy technology. Barbados has about 40 kW of photovoltaics (PV) installed along with an estimated 45,000 solar water heaters, Jamaica has incorporated hydro plants and wind turbines (approx. 20 MW); Aruba and Curacao have also installed wind turbine systems [3]. Guadeloupe has 90.4 MW of installed RE (26.3 MW for wind, 64.1 MW for photovoltaics) [12]. In the surrounding region, Argentina has installed about 11 MW of wind capacity and Costa Rica has a 20 MW wind plant [13]. The review of the literature indicates that there are no HRESs currently implemented in the Caribbean.

This study helps address this issue, by assessing the feasibility of a typical HRES combining wind and solar energy for electricity production in The Bahamas, providing answers to fiscal uncertainty and presenting a case study for investigation. The system's energy yield and financial performance is examined, and key financial indicators are identified and their impact on the system's feasibility is determined. This helps ascertain the suitability of such a system for electricity production in The Bahamas. Policy makers also need information on these types of systems in order to promote the mplementation of RE into the country.

2. Background

The Bahamas is an archipelago nation consisting of over 700 islands and cays with 11,400 km^2 of land area spread over 259,000 km^2 of ocean. The most recent census in 2013 estimates the population to be 377,400 and an average household size of 3.4 persons [14]. In 2014, the electrical energy use per capita was 5,700 kWh [15]. The country's primary energy producer is The Bahamas Electrical Company (BEC), which has 29 generation plants (28 diesel, 1 natural gas) spread across the country with a total installed capacity of 438 MW [16]. In addition to the BEC, Grand Bahama Power Company (GBPC) generates electricity. It has 9 diesel generators with an installed capacity of 98 MW generating power solely for the island of Grand Bahama [17]. In total The Bahamas has an installed electrical capacity of 536 MW [16] .

Similar to other Caribbean countries, The Bahamas can be characterized as having a small economy with a large gross domestic product (GDP) (2nd in the region) with a heavy dependence on imports. Fossil fuels account for about 23% of the annual national expenditure on imports. In 2010, US$2.8 billion was spent on fossil fuels [24].

In 2014 the BEC was almost subjected to an oil ban because of an unpaid debt (US$ 128 million) to its fuel supplier [18] [19] spending US$30-40 million per month [20]. The country has a yearly electrical production of 1,930 GWh, consisting of 99% from imported fossil fuels. In 2012, the United States and Canada, respectively, had an electrical energy use per capita of 12,954 kWh and 15,615 kWh [21], and produced 13% [4] and 63% [5] of electrical energy from renewable sources, respectively. The Bahamas in comparison has a much lower electrical energy use per capita (5,493 kWh in 2010), but less than 1% of its energy supply is from renewable sources [22]. In 2013, The Bahamas released a new energy policy that outlined the country's target of producing 30% of its energy from renewable sources by 2033 [23].

The Bahamas imports all of its fossil fuels [24] . The domestic production of energy through renewable resources could reduce price fluctuations and potential supply disruptions, providing more self-sufficiency and stable energy costs over time. RE alternatives could improve the country's energy security by diversifying its power generation choices and help offset the trade deficit caused by the reliance on fossil fuel imports [25]. The

Bahamas has established new RE polices and goals, but a lack of solar and wind databases exists for the country. Presently there are no solar radiation measurement sites, and a few wind measurement sites. The latter include two airports (Lynden Pindling National Airport (NAS) and Grand Bahama International Airport), and a third site established by the National Oceanic and Atmospheric Administration (NOAA) located on the island of Grand Bahama.

3. Approach and Methodology

In this paper, a proposed HRES system consisting of solar and wind energy to produce electricity for a typical community, which usually has about 500 homes, is considered. For analyses, the RETScreen software is used. An energy model is produced by describing the base loads of the households and the cost of electricity. Then, a proposed case is defined, which in this paper is the HRES. Initial cost analysis of the project is performed to determine investment expenses. This is followed by a greenhouse gas (GHG) emission analysis that uses a GHG emission factor to determine the carbon dioxide emissions avoided over the life of the system. Finally a financial, sensitivity and risk analyses are performed to estimate the economic feasibility of the HRES and how it is affected by certain variables.

Once the project location and site parameters are chosen (RETScreen uses monthly averaged data) different electrical load profiles can be specified. Thereafter, the type of equipment can be selected, such as what type of PV panels or wind turbines to be used in the analysis and its corresponding variables. During the cost analyses, initial and periodic costs can be defined and the parameters affecting the rate of GHG production. During the financial analysis, economic variables that affect the project over its life such as inflation, incentives, debts, etc. are chosen for the calculation of financial indicators to evaluate the project's feasibility. Finally, the sensitivity and risk analyses allow the uncertainties to be estimated for key parameters [26].

4. System Description and Data

4.1 *System and site description*

In this study a system comprising of multiple electrical power technologies (PV and wind) is considered. There are many configurations for RE mixes, from solar sources only and wind sources only, to more complex configurations that include solar, wind, hydro, geothermal, and/or tidal energy. All these merit consideration and are the subject of ongoing research [7] [10] [27]. The particular combination of solar PV and wind energy considered here for The Bahamas, is selected because sunshine and wind are abundant. Ultimately an optimization approach can be used to determine the most suitable options and configurations.

The site for the HRES is located on the island of New Providence in The Bahamas with the coordinates of 25.0°N and 77.5°W (latitude and longitude). The location for the study was chosen because it is the most populous island in the country along with current energy production issues and periodic load shedding. The system proposed is sized for a community of 500 homes (a typical size of a residential community in The Bahamas) where 95% are homes are modeled using a load profile of normal homes in The Bahamas and 5% of the homes are considered to be luxury homes with a different load profile. A normal home describes the average Bahamian household for the middle class, and constitutes the largest percentage of homes.A luxury home represents the average Bahamian household for the upper class. They represent the smallest percentage of Bahamian homes, yet they consume 2-4 times the electrical energy that normal homes do on a monthly basis. Both of these load profiles are combined into a single load profile (using weighted averaging).

The proposed system is assumed to cover the peak load of the community based on the load profiles in Fig. 1. Energy audits of 12 homes on New Providence (6 luxury homes and 6 normal homes) were conducted and the monthly electrical consumption load profiles were developed by an engineering consulting firm [2]. An average of the two categories is used in this study. Since RETScreen allows for only a single load profile, a profile that combines the monthly loads of luxury and normal homes is needed. For this combined case, shown in Fig. 2, the weighted average of the two load profiles is used to describe the load profiles of both luxury and normal homes in a single load profile.

There are no net metering policies or any type of renewable incentives in The Bahamas other than the reduction of import costs on solar equipment by 10%. In this study it is assumed that energy can be sold back to the grid and that excess energy sold to the grid is sold at \$0.12/kWh, which is approximately 30% of the current average cost including fuel surcharges. This is a net billing framework similar to a pilot program that was conducted on the island of Grand Bahama to determine if this type of policy is suitable [29].

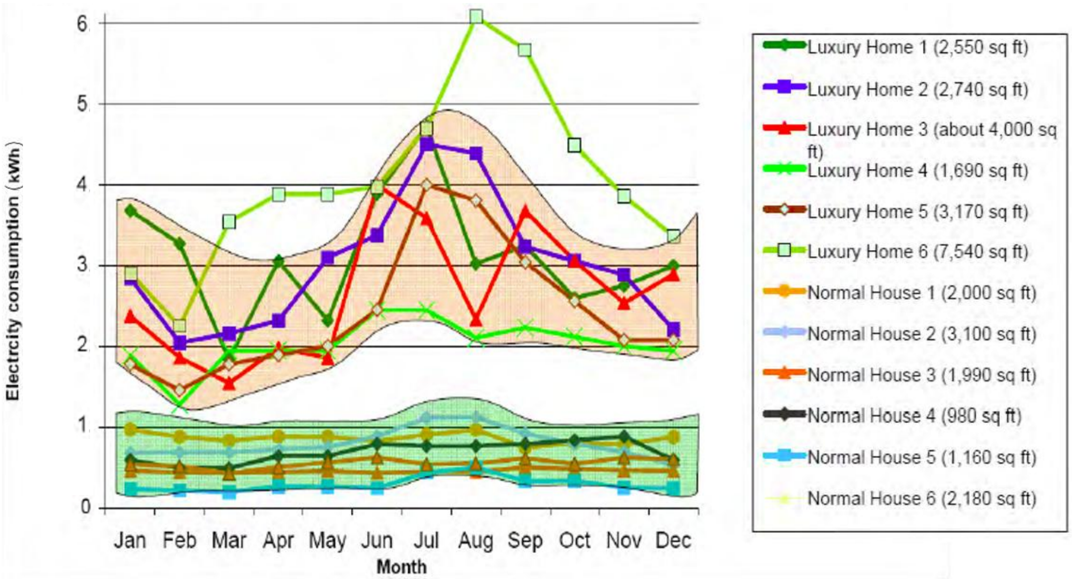

Fig. 1. Load curves of 12 audited households in The Bahamas showing monthly electrical consumption [28]. The points are joined with a line to help readers follow the trends.

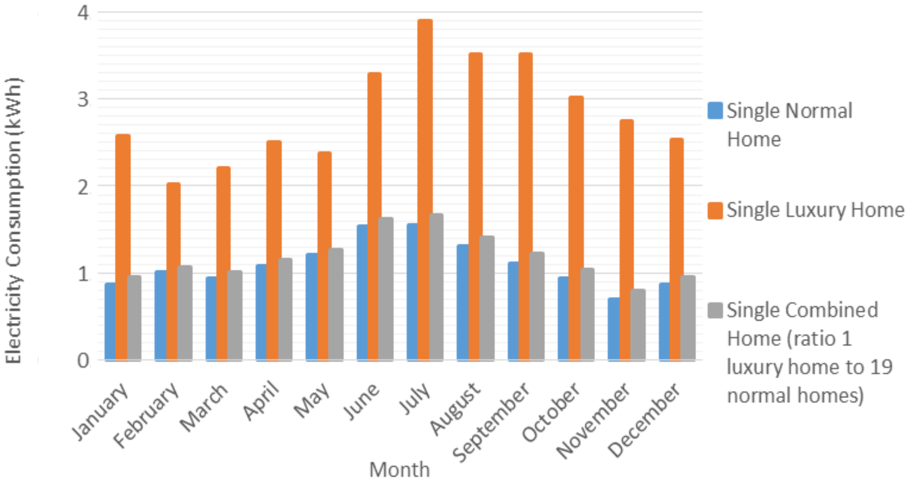

Fig. 2. Average monthly electricity consumption of normal and luxury homes including a combined weighted average load profile representing both types of homes in a single load profile.

4.2 Solar Data

As mentioned earlier, The Bahamas does not have any solar radiation measurement sites and thus access to reliable local data is limited. The solar data used for the present analysis is for Key West International airport in Florida, USA. These data are obtained from the National Solar Radiation Database (NSRDB) provided by the National Renewable Energy Laboratory (NREL). This dataset from Key West (24.55° N and 81.78° W) is in close proximity to The Bahamas (25.06° N and 77.33° W) where the change in lattitude is less than 1 degree. The variation in the amount of solar radiation incident on the earth in a day is negligible with respect to longitude between sites. The change in incident solar radiation due to the small change in lattitude between the sites is considered to be negligible. The close proximity leads to both locations having similar climatic conditions. Factors that affect the amount of solar radiation, such as cloud cover and total sunlight hours, are assumed to be similar for both locations over an extended period of time.

According to the NREL the NSRDB is Class I data which states that the dataset is complete and no interpolation or other methods are used to fill in data. Twenty years (1991-2010) of hourly recorded global horizontal irradiation (GHI) was accessed for time averaging. Monthly averaged GHI values are calculated as shown in Table 1 for use with RETScreen.

4.3 Wind Data

Wind data used in this study are taken from the Lynden Pindling International Airport in Nassau, Bahamas. This site is located on the same island as the planned HRES system. Fifteen years (2000-2014) of hourly recorded wind speeds are also time averaged to determine monthly average wind speeds. The wind speeds are measured at a height of 3 m. This height does not reflect the actual wind speed at the turbine's hub height and thus needs to be corrected. To account for this the power law for wind profiles is used to extrapolate the wind data. The data shown in Table 1 correspond to the height of 10 m (the height RETScreen uses for its analysis) and to the hub height (67 m) of the wind turbine used in this system, to estimate its capacity factor. The following wind profile power law relationship, which is a commonly used approach to extrapolate wind speeds to different heights [30] [31], is used:

$$\frac{u}{u_r} = \left(\frac{z}{z_r}\right)^{\alpha} \tag{1}$$

Here, u and z are the desired wind speed and height, respectively, while u_r and z_r are the initial wind speed and height, respectively. Additionally, α is the surface roughness coefficient, usually assumed to be 1/7, but in this analysis it is determined as follows:

$$\alpha = [0.37 - 0.088\ln(V_0)] / \left[1 - 0.088\ln\left(\frac{h_0}{10}\right)\right] \tag{2}$$

where V_0 and h_0 are the measured speed and height, respectively [30] [31].

Table 1. Monthly solar GHI and wind speed data used in RETScreen for energy analysis

Month	Daily GHI (kWh/m²/d)	Wind speed at 10 m height (m/s)	Wind speed at 67 m height (m/s)
January	3.75	4.9	7.6
February	4.58	5.0	7.7
March	5.65	5.6	8.5
April	6.50	5.3	8.1
May	6.74	4.9	7.6
June	6.56	4.5	7.1
July	6.63	4.6	7.1
August	6.28	4.3	6.8
September	5.52	4.0	6.4
October	4.71	5.0	7.8
November	3.91	5.4	8.3
December	3.41	5.2	8.0

5. Analysis

5.1 Energy model

Using climate data RETScreen estimates the electrical energy production from solar energy via the Duffle and Beckman equations. The total yearly energy that can be converted by the solar panels E_p can be expressed as a function of the solar collector area S and the annual average solar radiation on a tilted surface $\bar{H}_t$, as follows:

$$E_p = S\bar{H}_t \tag{3}$$

The converted energy $\bar{E}$ is determined as follows:

$$\bar{E} = E_p \eta_p \lambda_l \tag{4}$$

where η_p is the efficiency of the solar panels and λ_l is a factor that accounts for the miscellaneous losses of the system.

The electrical energy produced by the turbine is determined from Betz's expression for power based on kinetic energy:

$$P_t = \frac{1}{2} C_p A \rho V^3 \tag{5}$$

where C_p is the capacity factor of the wind turbine, A is the swept area of the blades, ρ is the air density and V is the wind speed at the hub height.

5.2 Details of HRES system

The solar part of the HRES system consists of a rooftop fixed mounting system. Since New Providence is a small island, land space is limited and rooftop PV is preferred in such cases. The modules are oriented south (azimuth = 0 deg. in the northern hemisphere) for yearly power generation with a tilt equal to the absolute value of the latitude (25.1 deg.) [32]. The solar panel type chosen for the system is a SunPower module, which produces some of the most efficient panels on the market [33]. The panel used in this study has an efficiency of 19.6% and a rated power of 320 W. Additional specifications are listed in Table 2. Each normal home is fitted with eight solar panels and each luxury home with ten according to the available rooftop space for each type of home. For the 500 homes, the total number of solar panels required is 4,150 and the overall installed capacity is 1,328 kW.

Table 2. Specifications of solar panel used in the study [34].

Item	Specification
Manufacturer	SunPower
PV Module Type	Mono-crystalline silicon
Model Number	SPR-320E-WHT-D
Power Rating	320 W
Efficiency	19.6%
Module Surface Area	1.62 m^2

The wind part of the HRES consists of a single wind turbine. New Providence is a small island with a dense population so land space is limited which restricts the use of multiple turbines. Additionally, the country's marine life is rich and includes one of the largest coral reef barriers in the world, restricting the use of offshore wind turbines. Other factors such as noise and aesthetics limited this study to the use of one turbine. For this study a Windtec manufactured turbine is used. This type of turbine is widely used in industry and is known for its reliability and versatility permitting operation in various types of climates and conditions. It is rated at 1,500 W and has specifications as listed in Table 3. The capacity factor, defined as the ratio of average power to the rated power output, is an indicator of a wind turbine's performance [37]. It also represents the ratio of the full load hours of annual production to the rated capacity. In practice this value falls between 20% and 40%. Various methods can be used to estimate capacity factor, but a simple approach that yields a realistic value of 35% is adopted here. For the 15 year dataset from the Lynden Pindling Airport, the percentage of hours at a particular wind speed is calculated for wind speeds up to 25 m/s. For example if 7% of the time the wind speeds are between 2-3 m/s, then the power curve of the turbine is used to calculate the capacity factor by determining the ratio of predicted power for the load hours to the rated power of the turbine.

Table 3. Specifications of wind turbine used in this study [34].

Item	Specification
Manufacturer	Windtec
Model Number	Windtec 1566 - 67
Power Rating	1500 kW
Capacity Factor	35%
Rotor Diameter	66 m
Hub Height	67 m
Swept Area	3421.19 m^2

In addition to the energy and cost variables, an emissions analysis is incorporated into RETScreen. For The Bahamas, the GHG emission factor used is 0.282 tCO_2/MWh [1]. The transmission and distribution losses are assumed to be 5% of the total electrical production.

5.2.1 *Cost Assumptions*

A NREL report benchmarked the installed price of solar photovoltaic (PV) systems in the first quarter of 2015 to be approximately US$3.09 per watt [36]. Including the import tax of 10% and value added tax of 7% for The Bahamas, the installed cost of solar PV is assumed to be US$3.98 per installed watt. Thus, the overall cost for PV for 1,328 kW is approximated to be US$5.39 million. The annual operation and maintenance cost for the PV system is taken to be US$21 per kW[36] which amounts to about US$28,000 per year.

For the wind turbine the installed cost is US$4.02 per installed kilowatt and the annual operation and maintenance cost for wind turbines is taken to be US$136 per kW in 2013 [37]. The operations and maintenance (O&M) costs amount to US$204,000 per year. The overall cost for the installed turbine of 1500 kW capacity is US$6.03 million. The overall costs of the HRES is therefore about US$11.3 million.

RETScreen calculates the internal rate of return (IRR) and simple payback period. This IRR is the rate that causes the net present value (NPV) to be zero. The assumptions for this financial analysis are that the inflation rate is 1.41%, which is the actual current inflation rate of The Bahamas, the project life is 20 years, and no incentives are applied other than the allowance of a net billing policy as described above. Fuel cost escalation rates of 0%, 5%, and 10% are considered in this paper, similar to rates considered in other studies [38] [39]. The case that produces the maximum NPV and minimum payback period will be discussed in detail.

5.2.2 *Sensitivity and Risk Analysis Considerations*

Because of the dynamic nature of the economy and projects of this type, a sensitivity analysis is performed for the economic indicators. RETScreen uses the Morris or one-at-a-time (OAT) method [40] to conduct the sensitivity analysis. One variable is allowed to change and the calculations are repeated for the particular parameter sought. For the sensitivity analysis, the NPV is assessed with a sensitivity range of 30% [41]. This means that each variable can change, but within the limits of a ±30%. The variables in this analysis examined are the electricity export rate and the initial costs of the HRES. For the risk analysis, the equity payback period and the NPV are considered. A range of 40% is applied to the parameters of initial cost, O&M cost, current electricity prices and electricity export rate. This range is similar to values used in other analyses reported in the literature [42]. Both the above ranges are assumed to provide a reasonable estimate of the possible variation in the Bahamian market. The cost assumptions used in this paper are levelized costs of electricity (LCOE) which has a variation of US$0.21 [36] for solar and US$0.80 for wind [38] globally, a 6% and 19% variation, respectively. Including the import tax of 10%, value added tax of 7% and cost assumptions that are unforeseeable, a 30% range is believed to be suitable. The risk analysis performed uses the Monte-Carlo technique with 500 steps for the NPV and IRR. Each variable varies simultaneously and independently within a given range under a normal distribution.

6. Results and Discussion

6.1 Overall Energy Performance

The HRES is estimated to produce 6,845 MWh per year having an electrical energy mix of 32.8% from PV and 67.2% from the wind turbine. Over the year 5,146 MWh is delivered to the 500 homes, 1,699 MWh is exported to the grid and 65 MWh is used from the grid. The system produces more electrical energy per annum than the yearly electrical energy requirements of the 500 homes (5,211 MWh), indicating that the system on average achieves a positive energy balance every year. Despite a positive electricity balance, electricity is still required from the grid (65 MWh) throughout the year, primarily due to periods when the system does not produce enough electricity. Energy storage may mitigate the use of electricity from the grid since the system does have a positive net energy balance for the year. Further studies of incorporating energy storage appears to be merited and may enhance the overall performance and feasibility of the HRES [44].

6.2 Fuel Cost Escalation Rate

A trend is seen with the NPV is always increasing and the payback period is always decreasing as the fuel escalation rate increases, as shown in Table 4. Therefore the lowest rate of 0% is discussed further. If the fuel cost escalation rate is greater than 0%,the economic potential of the system is predicted to increase as well.

Table 4. Effect of Fuel cost escalation rate on the NPV and equity payback period

Fuel cost escalation rate (%)	NPV (US$)	Equity payback period (years)
0	19.3	7
5	42.1	5.8
10	86.0	5.1

6.3 Economic Analysis

With the assumption that energy production is constant throughout the life of the system, the annual electricity export income is approximately US$203,927 with an annual savings valued at about US$1.87 million. This takes into account the fuel cost savings and electricity production income. The estimated equity payback period occurs at the beginning of year 7 leaving 13 years of the system's life for profit. At the end of the system's life, assuming no end of project life recovery costs, the NPV is estimated to be US$19.3 million which is larger than the initial investment of US$11.3 million and thus indicates that the system is economically feasible. The internal rate of return is evaluated to be 13% with a benefit-cost ratio (the ratio of the NPV to the initial costs) of 2.7.

It is noted that this HRES is not an optimized system, even though the results show that it is a viable option. The economic analysis shows that, even without a net metering policy or incentives, the HRES is still feasible. If incentives were to be introduced, the system has potential to be more lucrative with a shorter payback period.

6.4 System Emissions

For the GHG analysis, there is a net annual GHG reduction of 2,026 tCO_2 and over the lifetime of the system; a reduction of 40,523 tCO_2. This is equivalent to about 4,712 barrels of crude oil not consumed each year. The HRES does require some electricity from the grid, and the emissions associated with that amount to 25.2 tCO_2 per year.

6.5 Results of Sensitivity and Risk Analyses

The analyses in this project assesses how initial costs, electricity export rate (price sold to grid), and current electricity price (fuel cost-base case) affect the equity payback period and the NPV of the HRES.

Table 5 shows the effect of changing initial costs and electricity export rate on the NPV of the system. It can be observed that as the initial costs decrease and the electricity export rate increases, the NPV of the system increases. In the worst case scenario, when the export rate is –30% and the initial costs are +30%, the NPV is higher than the initial costs and indicates that the system is economically viable and profitable. Any scenario worse than this results in a loss, and the system is no longer economically feasible. In Table 6, a similar trend for NPV is observed, in that the NPV of the system increases when the initial costs decrease and the electricity prices increase. The main difference is that the electricity costs has a larger effect on the NPV. In the above cases even if electricity is sold at 30% cheaper than the case used in the financial analysis, there is always a net profit margin. Here, if there is a 30% reduction in the current costs, the project incurs a loss (highlighted) when the initial costs are equal to or greater than the estimated cost of the project. In the worst case scenario when the export rate is –30% and the initial costs are +30%, the NPV is much lower than the initial costs and the system is seen not to be economically feasible. It is also instructive to assess how both the export rate and the current electricity costs affect the NPV simultaneously. For this scenario (see Table 7), for all cases for which the cost of electricity is reduced by 30%, the system is not feasible and is visualized with the strikethrough values. Price fluctuations would need to be considered for implementing a HRES like this. A reduction in fuel costs of over 15% makes this system economically non-viable. From the sensitivity analysis it is determined that electricity costs, initial costs and export rates have the most impact on the NPV of the project.

In the risk analysis, the distribution containing the financial indicator's outcome is generated by using randomly selected values within a given range to simulate possible outcomes. This process involves two main steps. The first is that, for each variable, 500 random values are generated according to a normal distribution with a mean of 0 and a standard deviation of 0.33. Each random value is then multiplied by the related percentage of variability (±30% in this case) creating a matrix containing the percentages of variation that will be applied to the initial values.

Table 5. Sensitivity analysis results showing the change in NPV (million US$) with a ±30% change in both initial costs and electricity export rate.

		Initial cost (million US$)				
Electricity export rate (US$/MWh)		7.9	9.6	11.3	13.0	14.7
		-30%	*-15%*	*0%*	*15%*	*30%*
84	*-30%*	21.3	19.7	18.1	16.6	14.9
102	*-15%*	21.9	2.3	18.7	17.1	15.5
120	*0%*	22.4	20.9	19.2	17.6	16.1
138	*15%*	22.9	21.4	19.8	18.3	16.7
156	*30%*	23.3	21.9	20.4	18.8	17.2

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Table 6. Sensitivity analysis showing the change in NPV (million US$) with a ±30% change in both initial and current electricity costs.

		Initial cost (million US$)				
Current Electricity cost (US$/MWh)		7.9	9.6	11.3	13.0	14.7
		-30%	*-15%*	*0%*	*15%*	*30%*
224	*-30%*	13.1	11.5	9.97	8.39	6.81
272	*-15%*	17.8	16.2	14.6	13.0	11.5
320	*0%*	22.4	20.9	19.3	17.6	16.1
368	*15%*	27.1	25.5	23.9	22.3	20.8
416	*30%*	31.7	30.1	28.6	26.9	25.4

Table 7. Sensitivity analysis showing the change in NPV (million US$) with a ±30% change in both electricity export rate and current electricity price.

		Electricity export rate US$/MWh				
Current electricity Cost US$/MWh		84	102	120	138	156
		-30%	*-15%*	*0%*	*15%*	*30%*
224	*-30%*	8.83	9.39	9,.9	10.5	11.1
272	*-15%*	13.5	14.1	14.6	15.2	15.8
320	*0%*	18.1	18.7	19.3	19.8	20.4
368	*15%*	22.8	23.4	23.9	24.5	25.1
416	*30%*	27.4	28.0	28.6	29.1	29.7

These values are then used to calculate the 500 results of the Monte-Carlo simulation [26].The simulation results are displayed in the form of a histogram distribution using 20 bins and the relative frequency of the outcomes. For example if the first bin contains 100 of the 500 outcomes, then the frequency of the financial indicator for that bin is 20%. The level of risk for the histogram shows the upper and lower bounds for a confidence interval that is 1 minus the level of risk.

The impact values are calculated using a multiple linear regression model from the results of the Monte Carlo simulation. There are 500 values for the financial indicator associated with 500 values of each variable. The coefficients for each variable is calculated using the method of least squares [26]. The regression model is as follows:

$$Y = B_1X_1 + B_2X_2 + B_3X_3 + \cdots B_nX_n + \varepsilon \qquad (6)$$

where Y is the financial indicator being analyzed, X is an independent variable representing the input parameters, B is the coefficient for each input parameter and ε is the model error.

The impact values I are a standardization of the coefficients by applying the following formula:

$$I = \frac{s_{X_n}}{s_Y} B_{X_n} \qquad (7)$$

Here, s_{X_n} is the standard deviation of the 500 X_n values, s_Y is the standard deviation of the 500 Y values, and B_{X_n} is the coefficient of the input parameter.The values of I are then plotted on tornado charts in descending order.

Tornado charts are useful for illustrating these trends and are used here in Fig. 3. The tornado graphs show the impact, or how much of a variation of the financial parameter in question is explained by the variation of each input parameter in the risk analysis. Effectively the graph shows the effect of a one standard deviation increase of an input parameter. Figure 3 shows that the increase in cost variables affects the NPV in a negative way but an increase in the other variables affects the NPV positively.

It can be observed that the fuel cost is the most impactful variable. This further supports the sensitivity analysis results Initial costs provide the second highest impact. Figure 4 is a histogram from the Monte-Carlo simulation showing the frequency (percentage of the time) and the possible values the NPV will have over a ±30% range for the following variables: initial costs, electricity costs, O&M and electricity export rate. For a level of risk of 5% and confidence interval of 95%, the NPV falls between US\$13.9 million and US\$25.1 million. This shows the range of possibilities for the NPV while taking into consideration the ranges of the variables

The payback period is also of interest and is shown in Fig. 5. In this case, the initial costs and the fuel costs have the highest impact and roughly the same amount of influence but opposite. That is, an increase in initial costs increases the payback period, but an increase in current electricity prices reduces the payback period. Figure 6 shows the Monte-Carlo simulation results of the risk assessment for the payback period. For the same level of risk and confidence as applied for the NPV, the payback period most frequently falls between 0.1 and 9 years with the median of 7 years. It is thus likely that a project like this will incur an equity payback in under 10 years. For a range of possible scenarios, the HRES is shown to be feasible for most cases. The current electricity rate and electricity export rates are significant factors that will affect the feasibility of such a system

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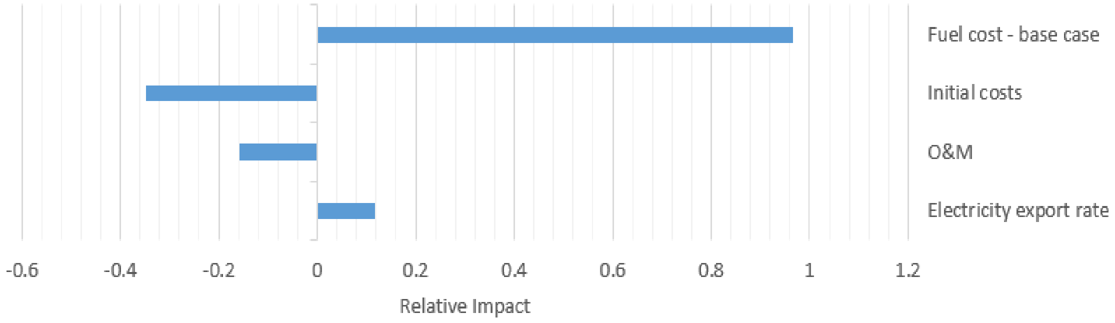

Fig. 3. Tornado chart showing the influence of variables on the NPV of the HRES

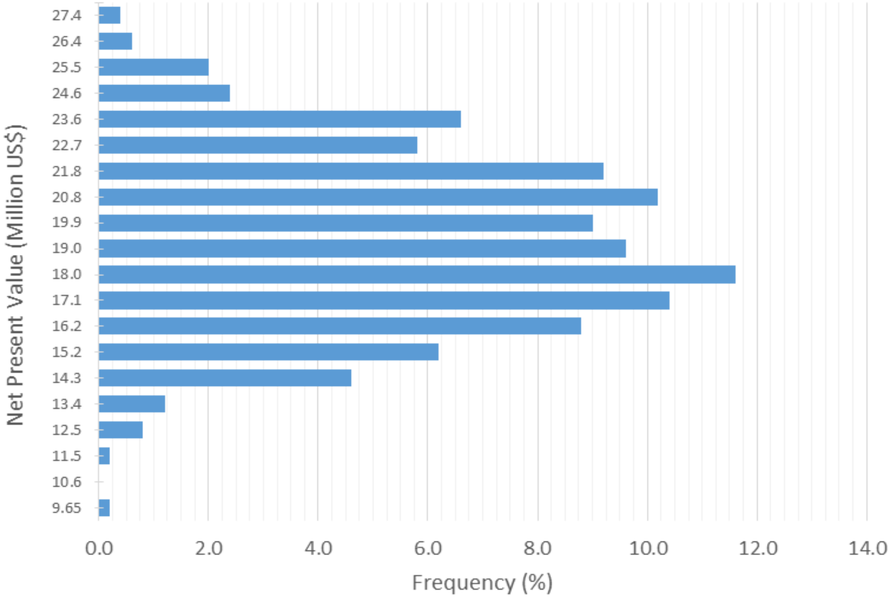

Fig. 4. Distribution of the 500 simulated NPV results showing the frequency (how often the NPV falls within a range). NPVs shown are the significant figures for the midpoint value of the bin. It helps to illustrate the results so the reader can follow the trends more clearly. .

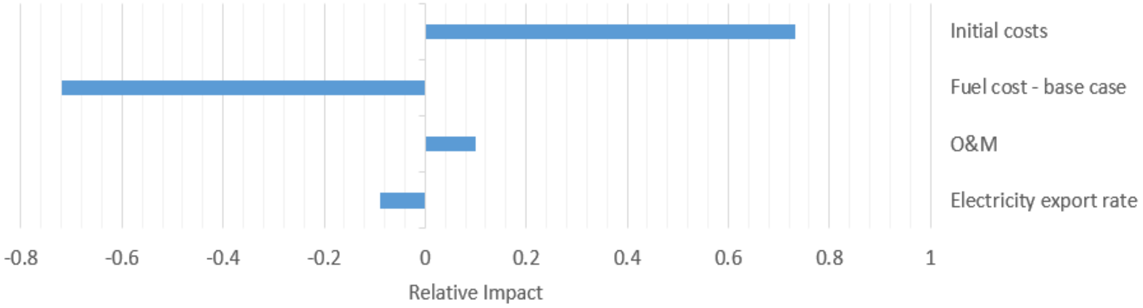

Fig. 5. Tornado chart showing the influence of variables on the payback period of the HRES

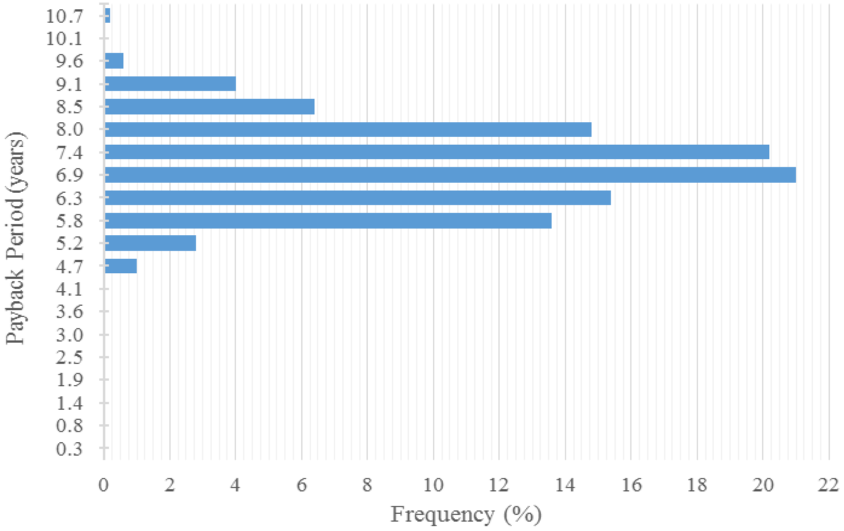

Fig. 6. Distribution of the 500 simulated payback period results showing the frequency (how often the NPV falls within a range). Payback period values shown are the significant figures for the midpoint values of the bin. It helps to illustrate the results so the reader can follow the trends more clearly.

7. Conclusions

The Bahamas has a RE policy with a target of poducing 30% of all energy using renewable sources by 2033, but has challenges in increasing the penetration of RE systems. In this paper, a feasibility analysis of power generation using a HRES that combines solar and wind is successfully performed, and demonstrates that the HRES can be an economically viable option. The results also provide policy makers and stakeholders with technical information and economic options through the use of sensitivity analyses. It also shows which factors impact the system the most and how. The main conclusions from the study are as follows.

The proposed combined power generation systemis determined to be feasible as it has a NPV of about US$24 million which is almost double the initial cost of US$12.6 million. The proposed system also produces enough energy to offset the 500 homes' annual energy usage of as well as export excess electricity to the grid. The equity payback period for the project is about 7 years which is a reasonable time period for RE systems.

The sensitivity analyses illustrated different possible scenarios, and can be seen as providing not only assessments of uncertainty, but also conceivable outcomes. In this paper the electricity export rate is US$ 0.12/kWh. The sensitivity chart allows for various scenarios to be observed while determining the limits of the viability of the system or a snapshot of its economic potentials.

In the risk analyses two variables that highly impact the feasibility of the system are the initial costs and the fuel cost in the base case (current electricity prices). It is seen that they somewhat offset each other, as they have opposite impacts of similar magnitudes for the payback period. However the NPV of the system is more than twice as dependent on the fuel costs. If current power generation prices are reduced, then the initial costs of the project must also be reduced in order for the project to remain feasible. Two other factors (electricity export rate and O&M costs) exhibit a similar relationship but the impact is of less importance. This is probably due to the fact that the fuel cost savings greatly outweigh the energy sold to the grid.

HRESs can be a viable application for achieving the energy targets of the Bahamas while being profitable economically. The outcomes support this idea. The sensitivity and risk analyses show to what level some non-controllable financial variables affect the implementation of HRESs. The incorporation of fiscal incentives may further increase the feasibility and thus the integration of HRESs.

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