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Evaluation of small wind turbines in distributed arrangement as sustainable wind energy option for Barbados

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Abstract

The island of Barbados is 99% dependent on fossil fuel imports to satisfy its energy needs, which is unsustainable. This study proposes a 10 MW distributed wind energy scheme using micro wind turbines (WT) of horizontal (HAWT) and vertical axis (VAWT) configurations. These units are rated less than 500 W, and the scheme is hereafter referred to as mWT10. mWT10 is compared to the proposed 10 MW medium WT farm by the Barbados Light & Power Company (BL&P). The economic bottom line is the levelized cost of electricity (LCOE). The results highlight the BL&P proposal as the best economic option at BDS$0.19 per kWh, while that of both mWT10 configurations exceeds the conventional cost of BDS$0.25 by two to nine times. This is attributed to significantly higher relative installation and operational costs. However, the financial gap between mWT10 LCOE and the retail price of electricity is much smaller due to a large fuel surcharge passed on to each customer. Annual additional benefits of using wind energy include: greenhouse gas emissions savings of 6–23 kt of carbon dioxide; and anavoided fuel costs of BDS$1.5–5.3 million.

The distributed mWT10 using HAWTs competes directly with the BL&P farm, however, it provides these benefits without the visual or ecological impacts of the larger machines. Conversely, VAWTs have features that favour a visually discrete and widely repeatable scheme but suffer relatively high costs. Therefore, this study illustrates the great potential of small wind turbines to be competitive with conventional wind farms, thus challenging the small wind industry to meet its potential by producing reliable and robust machines at lower cost.
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Keywords: Engineering for sustainable development; Renewable energy; Wind energy; Micro wind turbines; Sustainable energy systems; Distributed generation

1. Introduction

The 431 km^2 Caribbean island of Barbados is located at 13°04′, −59°29′ (Grantley Adams International Airport, GAIA) and is 99% dependent on imported fossil fuels to meet its energy needs, half of which are used in electricity generation. This dependence on a non-native, non-renewable fuel, which decreases in availability and increases in price every year, leaves Barbados and other small states in a precarious position. Moreover, Barbados must trade internationally using foreign exchange obtained from its reserves. Consequently, large expenditures on fuel put a strain on these savings.

The privately owned Barbados Light & Power Company (BL&P) is the original and sole electricity service provider. In 2005, there was a peak demand of 154.20 MW, supplied by 239.10 MW total installed capacity [1]. Customers are charged a base energy price and a fuel adjustment clause (FAC), which allows BL&P to recoup some expenses from the increasing fossil fuel costs. In 2005, the FAC averaged BDS[1]$0.17 per kWh.

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[1] The Barbados dollar, BDS$, is used throughout unless otherwise specified, at an exchange rate of US$1.00 to BDS$1.98 and €1.00 to BDS$2.54.

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The BL&P conventional generating fuel mix of heavy oil, Diesel and kerosene releases 0.77 kg of carbon dioxide (CO_2) per kWh, resulting in the emission of 760 kt of CO_2 in 2005.

The Intergovernmental Panel on Climate Change (IPCC) indicates that the increase in global CO_2 emissions since the beginning of the industrial age has resulted in the highest concentration in the last 420,000 years and likely in the last 20 million years [2]. World Data Center for Greenhouse Gases (WDCGG) measurements taken at the most upwind location in Barbados of Ragged Point show an atmospheric concentration of 380.7 parts per million (ppm) CO_2 in December 2005. Therefore, climate change on a global state has effects on Barbados, and thus, the issue is more whether mankind can afford to continue burning fossil fuels than how much is actually left to be consumed [3].

Herman Daly argues the concept of quasi-sustainability [4], where a renewable alternative is developed simultaneously with the exploitation of a non-renewable such that when the latter reaches the end of its life, the former is in a position to substitute. Practically however, a historical lock into fossil fuel based generation has implied a lock out of generation by other methods, such as renewables [5]. Decommissioning of aging generating plants, most recently in 2004 by BL&P, provides the opportunity necessary for renewable energy converters to be implemented [6]. The Government of Barbados (GoB) has a target of 40% of its energy needs to be met by renewable sources by 2025 [7].

Barbados benefits from north easterly trade winds, allowing wind energy conversion technologies to be technically feasible. The wind turbine (WT) axis of rotation may be aligned vertically, for vertical axis WTs (VAWTs) or, more commonly, horizontally, for horizontal axis WTs (HAWTs). The full range of WTs covers many power levels, from large, multi-megawatt utility scale machines to micro machines of less than 100 W for battery charging.

The term "intermittent" is used interchangeably with "variable" to describe the energy output of wind and other renewable energy converters. However intermittent sources start and stop unexpectedly, whereas variable ones have predictable, though non-constant, output [8]. Furthermore, wind and other renewable energy based electricity systems have fixed and dependable fuel costs, as the natural resource is fully assessed at the time of deployment, whereas fossil fuel based systems depend on a price variable input. This is illustrated by the inclusion of the variable FAC to the base energy cost, yielding a fluctuating retail energy price.

BL&P recently concluded the stakeholder consultation phase of a 10 MW medium WT (MWT) farm in the Lamberts East area of the northern most parish, St. Lucy. The BL&P proposal would consist of eleven 900 kW machines with rotor diameter up to 56 m on towers up to 55 m above ground level (AGL), arranged in line along a topographical ridge. The farm would be located 1.50 km inland from the windward, east coast. The farm will occupy a strip of land of 1.50 km in length. The justification for the scheme is deferral of CO_2 emissions [9], and it is expected that the farm would produce 30.03 gigawatt hours (GWh) annually.

The alternative 10 MW scheme proposed herein capitalizes on the benefits of distributed generation and the flexibility of small machines. The scheme would utilize many micro WTs with rating <0.50 kW [10] each, (mWT10). It is envisioned that this initiative be spearheaded by BL&P, mounted on their utility poles, operating at a hub height of 10 m without the option of providing back-up energy. Both schemes constitute 6.49% of the 2005 peak demand. mWT10 is evaluated using micro HAWTs and VAWTs.

mWTs are not generally deployed in utility scale initiatives, due in part to low investment devoted to making these machines competitive on a feature and reliability basis. Thus, utility skepticism and low confidence in the ability of the machines to deliver as advertised detracts from mWT10. Consequently, this study gives insight into what is possible, if the appropriate investments in reliability, quality and performance were made. The International Energy Agency (IEA) has recognized the current industrial deficiencies and large potential and is seeking to bridge this gap [11]. Recognizing the aforementioned technological shortcomings, where possible, WTs accredited by the UK Department of Trade and Industry (DTI) Low Carbon Buildings Programme, formerly the Clear Skies programme, are used.

2. Wind resource assessment

The wind site evaluation technique used is given below:

(1) Wind speed measurements were grouped by the number of occurrences in a particular wind speed class to determine the frequency distribution (Fig. 1).
(2) A Weibull probability distribution was fitted to the frequency graph (Fig. 2), and the average and most probable wind speeds are derived, all using the following equations [12].

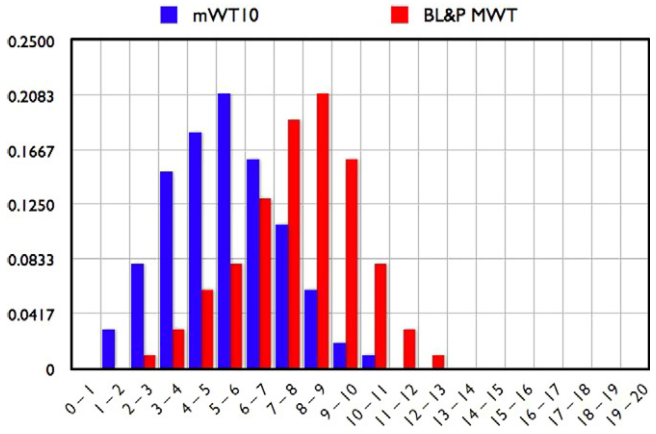


Fig. 1. Frequency distribution of CIMH and BEI data.

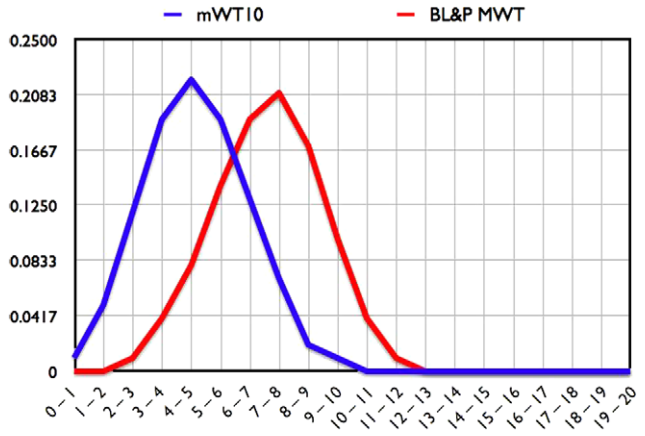


Fig. 2. Weibull distribution fitted to CIMH and BEI data.

- The general Weibull distribution equation is given by:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

where k and c are given by [12]:

$$k = \left(\frac{\text{Data measured standard deviation}\sigma}{\text{Data measured mean value } v_{\text{mean}}}\right)^{-1.086} \tag{2}$$

and

$$c = \left(\frac{\text{Data measured from mean value } v_{\text{mean}}}{\Gamma\left(1+\frac{1}{k}\right)}\right) \tag{3}$$

where $\Gamma\left(1+\frac{1}{k}\right) = \left(\frac{1}{k}\right)!$ from the relation of the Gamma function to the factorial.

- The most probable wind speed v_{mp} [12] is given by

$$v_{\text{mp}} = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \tag{4}$$

where c is the Weibull distribution scale factor; and k is the Weibull distribution shape factor.

(3) The power density (W/m^2) is given by the particular wind speed occurring, $f(v)$; Betz' limit; and the wind speed to power relationship (Fig. 3).

- The wind speed to power relationship is:

$$P = \frac{1}{2}C_p\bar{\rho}v^3 f(v) \tag{5}$$

where C_p is the power efficiency of the rotor, the maximum value of which is the Betz Limit, 16/27; $f(v)$ is the Weibull derived probability of a particular wind speed occurring; and $\bar{\rho}$ is the corrected air density.

- The corrected air density is given by [13]:

$$\bar{\rho} = \frac{\overline{P}}{R_{\text{d}}T} \tag{6}$$

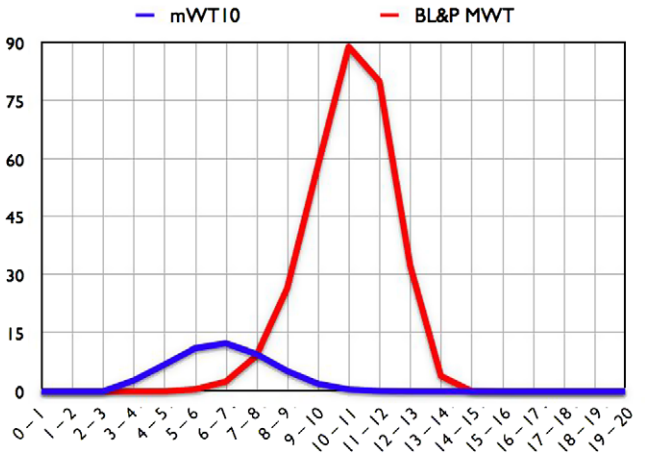


Fig. 3. Power density (W/m^2) associated with estimated wind resources for mWT10 and BL&P.

where $\overline{P}$ is the average monthly air pressure; R_{d} is the dry air constant, 287 J/kg K; and T is the monthly average air temperature (K).

- The energy output is zero below the machine cut in speed. It is assumed that positive energy output starts immediately when the wind meets this speed and that the WT performs at the Betz' limit.

(4) The cumulative power density is the sum of the power densities over each wind speed class (Fig. 4). Multiplication by the rotor swept area yields the power output.

(5) The annual energy output was determined by multiplying the power output by the 8760 h in a year.

The final annual yield (FAY) is a measure of the conversion efficiency from the input natural resource to the output electrical energy. It internalizes all losses and is modified from a solar photovoltaics (PV) performance assessment metric [14].

$$\text{FAY} = \frac{\text{Actual energy out } (\text{kWh}_{\text{ac}})}{\text{Aggregate nameplate rating of farm } (\text{kW}_{\text{p}})} \tag{7}$$

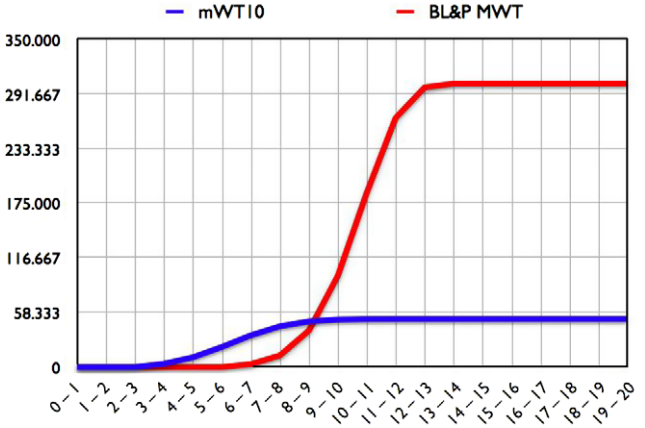


Fig. 4. Cumulative power density (W/m^2) associated with estimated wind resources for mWT10 and BL&P.

Capacity credit (CC) is the amount of installed conventional power that can be replaced/avoided by wind [15] and is approximated by

$$\mathrm{CC} = \frac{32.8}{0.306+\delta}\frac{\mathrm{CF}}{R_{\mathrm{system}}}\left(1+3.26\delta \mathrm{e}^{-0.1077(0.306+\delta)(x-1)}\right) \quad (8)$$

where x is the penetration level of wind as a percentage of peak load (6.94% for mWT10 and BL&P), $x > 1.00\%$; δ is the dispersion coefficient, taking values of 0 and 1 for perfect spread (assumed in the case of mWT10) and no spread (assumed in the case of BL&P); R_{system} is the reliability of the conventional electrical grid system as a percentage (99.97% for BL&P network); and CF is given by

$$\mathrm{CF} = \frac{\text{Measured annual energy output (kWh)}}{\text{Ideal energy output if machine/farm operated at rated power (kWh)}} \quad (9)$$

3. Wind farm proposals

The wind resource assessed as above using BEI data at 40 m AGL for the Lamberts East farm was compared to the findings of the original report. For mWT10, the hourly average wind speed data measured at GAIA at 10 m AGL for the period 1991–2005 was used. The cut in wind speeds are taken as 5 m/s for MWTs, 3 m/s for mWT10 HAWTs and 2 m/s for mWT10 VAWTs as indicated by specific unit power curves. From the data, there will be no output from Lamberts East 9.89% of the time, while for mWT10, it is 10.93% for HAWTs and 2.93% for VAWTs. The cut out speed for the WTs is not met in either proposal. Table 1 indicates that the most probable wind speed for mWT10 is 2.56 m/s lower than that for the proposed Lamberts East farm, attributed to the former operating 10 m AGL relative to the latter at 55 m.

Using rotor diameter has been determined to be a good proxy for determining power production [16]. The combination of estimated power output and rated capacity of the machine yields the FAY, with higher values indicating a better resource to machine match. Fig. 5, with 7* indicating a VAWT, illustrates the FAY of each machine under study, with the highest (circled) values denoting the ones most suitable to the estimated resource. Notably, the mWT with the best FAY competes directly with the FAY of larger ones, indicating that despite the overall wind resource being weaker, the conversion efficiency is still high. In estimating the performance of mWT10, the VAWT and HAWT with the best FAY were chosen.

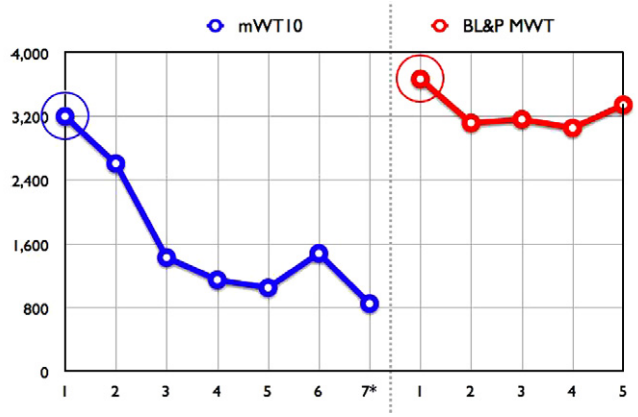


Fig. 5. FAY profiles of BL&P MWTs and mWT10 WTs.

Table 2 indicates that MWT and mWT10 HAWTs outperform the mWT10 VAWTs. This is due to the power production being proportional to swept area which, for VAWTs is small, on account of their physical configuration. The result is a flatter power curve at low wind speeds relative to HAWTs.

Incorporating 10 MW of wind into the BL&P generation mix of fuel oil, diesel and kerosene burning generators defers 0.77 kg CO_2 per kWh associated with using the fossil fuels.

The external emissions cost associated with onshore wind energy (800 kW turbines operating at CF = 20%) is given as 0.0105 kg/kWh GHG [17]. Small WTs have three times the embodied life cycle energy costs of MWTs per unit [18] and serves as an energy guideline in the absence of more specific data. Table 3 indicates the extent to which the wind proposals defer GHG from atmospheric release. The deferral of 6.29–23.59 kt of CO_2 per annum illustrates one of the major points in favour of wind deployment currently.

Much of the embodied energy in WTs is not widely available or well publicized, despite WT energy performance being closely linked to this step [19]. Consequently, specific energy payback times for the wind resource in Barbados are not readily attainable.

The economic evaluation of the wind proposals used the net present value (NPV), internal rate of return (IRR) and payback period to give a balanced representation of the proposal performances. The metrics are calculated by

Table 1
Wind resource characteristics for BL&P and mWT10 schemes

Parameters	BL&P	mWT10	Δv
c	4.32	2.89	
k	7.81	5.25	
v_{mean} (m/s)	7.81	5.25	2.56
v_{mp} (m/s)	7.35	4.53	2.82
σ (m/s)	2.03	1.98	0.05

Table 2
Performance values for BL&P and mWT10 schemes

Parameters	BL&P	mWT10	
		HAWT	VAWT
Annual energy output (GWh)	30.03	32.07	8.55
FAY ($\mathrm{kWh_{ac}/kW}$)	3003.00	3 207.40	854.53
CC (%)	41.04	39.26	10.46
CF (%)	34.63	36.61	9.75

Table 3
Emissions savings for BL&P and mWT10 schemes

Parameters	BL&P	mWT10	
		HAWT	VAWT
Annual energy output (GWh)	30.03	32.07	8.55
Deferred emissions (tonnes CO_2)	23,033.01	24,600.97	6554.26
Emissions costs (tonnes CO_2)	315.32	1010.34	269.18
Net emissions (tonnes CO_2)	22,717.72	23,590.63	6285.08

$$\mathrm{NPV} = K + \sum_{t=1}^{25} \frac{\mathrm{FV}_t}{(1+r)^t} \tag{10}$$

where K = initial investment; r = interest rate, 10%; and FV_t is given by

$$\mathrm{FV}_t = P\left(\frac{(1+r)^t - 1}{r}\right) \tag{11}$$

where P = present revenue carried forward to year t.

$$\mathrm{IRR} = r : \mathrm{NPV} = 0 \tag{12}$$

The economic payback period is the time required for the initial investment to be recouped and is the year in which the cumulative annual cash flows move from net negative to net positive.

The levelized cost of electricity (LCOE) is the break even price for economic viability of the system, given by

$$\mathrm{CRF} = \frac{[r(1+r)^t]}{[(1+i)^t - 1]} \tag{13}$$

where $t = 20$ years for WTs; and $i = r$, r as before.

The total installed costs of €900–1150 per kW are used for onshore MWTs, with O&M costs strongly linked with machine age, and given at €0.012 per kWh for the 20 year system lifetime [16]. Using worst case costs, the Lamberts East farm costs BDS$29 million with annual O&M expenses of BDS$915,000 associated with the expected 30.03 GWh output. Total installed costs (including power conversion electronics) of CAD$[2] 5000–6400 per kW, with annual O&M of CAD$40–130 are used, corresponding to machines rated 0.30–1.00 kW. These Canadian Wind Energy Association (CanWEA) figures are consistent with the DTI Clear Skies programme estimate of £3000 per kW installed. The worst case total installed cost is approximately BDS$106 million. Annual O&M expenses are BDS$2 million.

The wind proposals are evaluated economically over two cases. The base case incorporates only revenues from the wind farm energy sales. Table 4 shows that the MWT farm has a lower annual energy cost relative to conventional, and to the other schemes.

For mWT10, the cost of electricity surpasses the conventional cost by almost two times for HAWT, and over nine times for the VAWT system. This is attributed to the capital outlay and annual costs of mWT10 being 3.61 and 2.34 times higher, respectively, than the MWT scheme, outweighing the benefit of higher energy output.

Table 4
Economic performance of base case BL&P and mWT10 schemes

Parameters	BL&P	mWT10	
		HAWT	VAWT
Base case			
NPV @ $r = 10\%$ (BDS$)	565,057,830.81	584,586,785.16	−95,679,592.86
IRR (%)	64.73	23.12	–
PB (years)	3	6	> 20
LCOE (BDS$ per kWh)	0.19	0.54	2.04

The second case internalizes the externalities of electricity generation. Externalities are costs that are incurred by an activity that are not included in the pricing structure of the activity causing them [20], and their inclusion is a commitment to the "polluter pays" principle [21]. Table 5 shows the externalities related to each fuel type [22], with the BL&P generation mix assumed to be the average of the oil and gas values. Onshore wind energy externalities are inversely proportional to CF as well as to the nominal power rating of turbine [22]. Externalities, however, have been argued to be very location specific [23]. Consequently, these Euro-centric values are used in a Barbadian context only in an illustrative capacity. The average price for a tonne of carbon over the last hundred days on the open market remains at €7.55, however €19.00 per tonne is considered a mainstream estimate of the marginal avoidance cost to achieve Kyoto Protocol targets [22]. The effects of externalities on economic performance consider that the credits are sold in the current market. Table 6 indicates that the wind schemes are marginally affected by including externalities. This is due to the low negative costs associated with wind fuelled electricity generation and the low market price for their deferred carbon emissions. Including generation and climate change externalities individually into BL&P figures would raise the cost of conventional generation to BDS$0.28 and BDS$0.27 per kWh.

Given that these external effects are additive, the true cost of electricity generation in Barbados should be BDS$0.30 per kWh.

Similarly, since the deferred costs externalities can be combined, new LCOEs of BDS$0.16 for the Lamberts farm, BDS$0.49–0.50 for mWT10 using HAWTs and

Table 5
Externality costs of electricity generation by fuel

Generating fuel	€per kWh	BDS$ per kWh
Oil	€0.0170	$0.0400
Gas	€0.0060	$0.0200
Onshore wind @ CF = 20%	€0.0052	$0.0133
BL&P generation	€0.0115	$0.0300
Climate change effects due to CO_2 emission (/tonne CO_2)	€19.00	$47.48

[2] Canadian Dollar (CAD); €1=CAD$1.54.

Table 6
Economic performance of base case + externalities for BL&P and mWT10 schemes

Parameters	BL&P		mWT10	
	Conventional	MWT farm	HAWT	VAWT
Base LCOE (BDS$ per kWh)	0.25	0.19	0.54	2.04
Conventional generation	0.28			
− Wind generation		0.19	0.54	2.04
+ CO_2 costs/benefits	0.30	0.18	0.53	2.03

BDS$1.85–1.87 for mWT10 using VAWTs are obtained. Consequently, mWT10 is still uncompetitive.

4. "What-if" scenarios

The "What-if" analysis was designed to investigate how the LCOE changed with input variations, such as: ±3 m/s average wind speed change; lowered installation and O&M costs and using WTs rated 0.50–1.00 kW each.

From Eq. 5, WT output power is very sensitive to small resource changes. Since the mWT10 data was taken at GAIA only, and extrapolated broadly around the island, the actual wind resource experienced by the WTs in distribution will likely vary from the estimate. Table 7 shows that the LCOE does not decrease as much with higher wind speeds as it increases with lower ones. mWT10 by VAWT is the worst performer while the relative changes of the schemes using HAWTs is low, especially at wind speeds above the reference.

The installation cost was reduced to illustrate the degree of LCOE response. For mWT10, the installation is expected to be repeatable since it uses the utility poles. Additionally, the existence of poles eliminates the tower costs from the system configuration. Table 8 indicates that the reduced O&M costs have a greater impact on LCOE than reduced installation costs. This is due to the higher relative impact of reducing annual O&M costs by BDS$1.49 million for 20 years over a one time reduction of installation cost of BDS$20 million. Fig. 6 gives the relative impact of the preceding two "what-if" cases. It can be seen clearly that the HAWT schemes are consistent performers over many of the scenarios. With additive cost components, the best LCOE for the Lamberts East is

Table 7
"What-if" wind speed changes in the BL&P and mWT10 schemes?

All LCOE values in BDS$/kWh	BL&P	mWT10	
		HAWT	VAWT
Decrease v_{mean} by 3 m/s	0.87	2.02	7.20
Decrease v_{mean} by 2 m/s	0.47	1.56	5.53
Decrease v_{mean} by 1 m/s	0.28	0.92	3.36
Increase v_{mean} by 1 m/s	0.13	0.34	1.30
Increase v_{mean} by 2 m/s	0.09	0.23	0.86
Increase v_{mean} by 3 m/s	0.07	0.16	0.60

Table 8
"What-if" the WT install and O&M costs are reduced?

"What-if" case	BL&P	mWT10	
All LCOE values in BDS$/kWh		HAWT	VAWT
€900 per kW MWT install	0.16		
CAD$5000 per kW mWT10 install		0.45	1.72
CAD$40 per kW mWT10 O & M		0.43	1.63

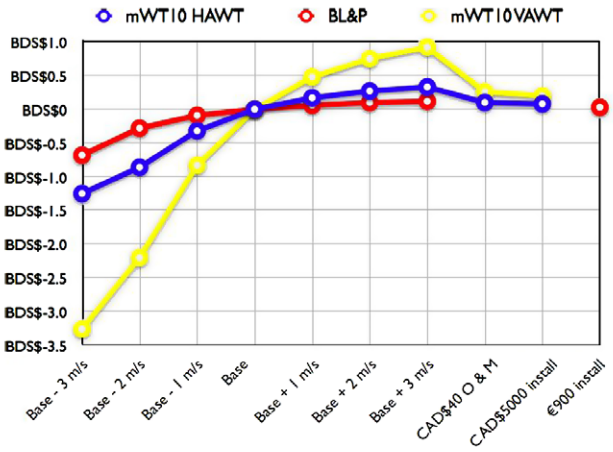


Fig. 6. Change in LCOE with "what-if" various wind speeds and lower capital outlay.

BDS$0.15 per kWh. For mWT10, the costs are BDS$0.42 (HAWT) and BDS$1.62 (VAWT), each higher than conventional by 68% and 548%, respectively. Incorporating the FAC for retail electricity pricing, customers pay BDS$0.37 per kWh. Now, mWT10 only exceeds retail price by 14% and 338% for HAWT and VAWT, respectively. Thus, including the FAC contributes significantly to closing the price gap and illustrates the true costs of conventional generation are high and are passed directly onto the customers, constituting a large burden.

Larger WTs are generally better designed and built machines, with better power electronics for easier grid integration, addressing most of the technological shortcomings of the micro machines. Therefore, they may be more suited to a distributed scheme as proposed. The economic study and both preceding "what-if" scenarios were repeated for machines of 0.50–1.00 kW. Table 9 shows that using larger turbines gives a better base case performance, however, it is still not competitive with the MWT farm or conventional generation. Fig. 7 indicates that the relative change in LCOE with wind speeds and installation costs appears to be lower for mWT10, giving confidence in price stability under varying conditions. mWT10 with HAWTs is marginally worse in its variation compared to the MWT farm, with the VAWT scheme showing poor performance overall but responding significantly and positively to wind speed increases.

Combining all cost components, mWT10 using HAWTs has an LCOE of BDS$0.35 and BDS$1.02 per kWh using VAWTs. Including the FAC to determine retail price, the

Table 9
"What-if" mWT10 used 0.50–1.00 kW WTs?

Parameters	BL&P		mWT10	
	Conventional	MWT farm	HAWT	VAWT
Base LCOE (BDS$ per kWh)	0.25	0.19	0.46	1.30
Conventional generation	0.28			
− Wind generation		0.19	0.46	1.29
+ CO_2 costs/benefits	0.30	0.18	0.45	1.28
Decrease v_{mean} by 3 m/s		0.87	1.71	4.46
Decrease v_{mean} by 2 m/s		0.47	1.32	3.50
Decrease v_{mean} by 1 m/s		0.28	0.78	2.13
Increase v_{mean} by 1 m/s		0.13	0.29	0.82
Increase v_{mean} by 2 m/s		0.09	0.19	0.55
Increase v_{mean} by 3 m/s		0.07	0.13	0.38
€900 per kW MWT install		0.16		
CAD$5000 per kW mWT10 install			0.38	1.09
CAD$40 per kW mWT10 O & M			0.36	1.03

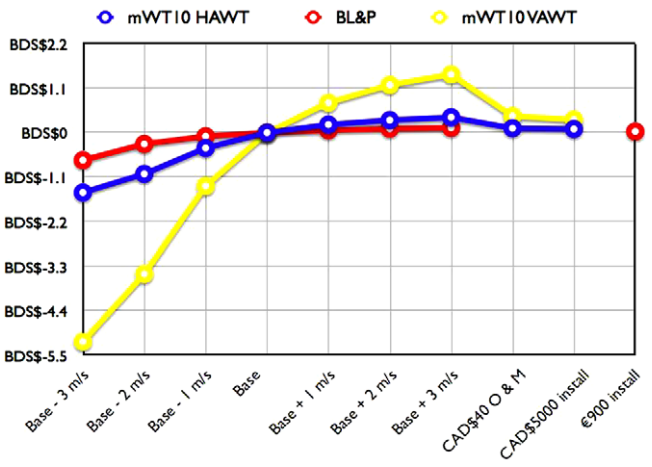


Fig. 7. Change in LCOE with "what-if" various wind speeds and lower capital outlay using 0.50–1.00 kW WTs.

gap closes from 40% and 420% to −5% and 308% for HAWTs and VAWTs, respectively. Thus, the LCOE for mWT10 with HAWTs is less than the retail price of electricity. In general, positive scenarios lower the LCOE by less of a proportion than negative scenarios raise it. This may be indicative of an asymptotic LCOE for the wind schemes as proposed, such that each additional kWh out, or dollar saved has little or no positive impact on cost. Consequently, there may be implications for which cost-saving measures are implemented based on impact on returns.

5. Sustainability discussion

Sustainable engineering initiatives involve holistic, systems level design, with consideration of how appropriate the project is as it relates to the wider society, economy and environment. Ultimately, the aim of any project is to solve as many problems as possible without creating any new ones [24].

Economic sustainability is often overlooked in the context of sustainable development and often is too much of the focus of conventional thinking. Under NPV, IRR and payback period, mWT10, except mWT10 using VAWTs, and the Lamberts East schemes perform positively. Wider, long term economic sustainability includes the preservation of local foreign currency reserves by deferring the purchase of non-native fossil fuels. A fuel cost of BDS$0.18 per kWh of electricity generated by conventional means is used. Table 10 illustrates that both wind schemes defer fuel expenditure. These avoidances are equivalent to 0.86–3.23% of the total fuel cost, based on 2005 BL&P expenditure of BDS$177,000,000. In all cases, this impact on the total fuel expenditure of BL&P is minimal.

Fig. 8 shows how closely the FAC follows overall fuel expenditure. Consequently, decreasing the fuel expenditure on account of the presence of renewables in the generation mix could stabilize the FAC in the near term, with a potential for decreasing it over the long term as the renewable penetration increases. This positive impact would be to the benefit of all customers.

The strong performance of the MWT farm creates a positive LCOE differential relative to conventional generation. This added flexibility allows wind to offset more expensive, though technically feasible technologies, such as PV. The ability to diversify technologies using generators with complementing time scales of operation would enhance the security of the primary energy supply [25].

Table 10
Avoided fuel costs associated with BL&P and mWT10 schemes

Parameters	BL&P	mWT10	
		HAWT	VAWT
Annual energy out (kWh)	30.03	32.53	8.56
Avoided fuel cost (BDS$)	5,343,921.20	5,707,706.12	1,520,663.31
% of 2005 Expenditure	3.02	3.23	0.86

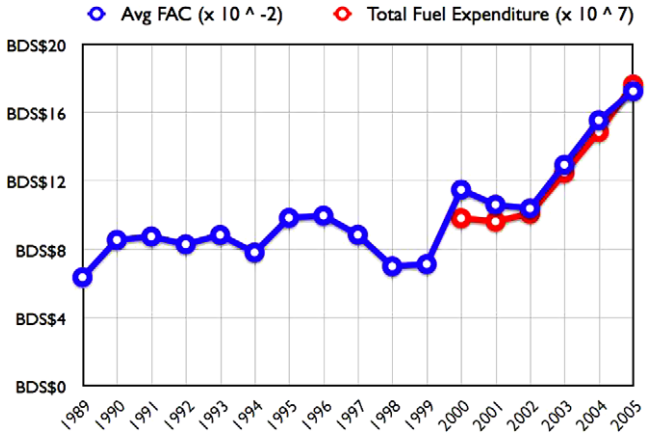


Fig. 8. Variation of FAC with total fuel expenditure.

The high cost of the wind schemes constitutes a large financial outlay for BL&P. The Caribbean Renewable Energy Development Programme (CREDP), operated under the Caribbean Community (CARICOM), provides support to eligible renewable energy projects, such as grid connected wind projects, contingent on specific project qualification criteria being met. These include: after tax return on investment >15%, NPV > 0; net foreign exchange savings; net reduction in GHG; projected LCOE less than avoided cost of electrical energy and capacity; and a strong potential for duplication. The Lamberts East scheme meets the CREDP criteria in full, while mWT10 does not, based on its higher LCOE relative to conventional generation. Project duplication is important so that other member states benefit easily and quickly from using renewable energy based fuels for their electricity production. It has been demonstrated that Barbados has the requisite combination of wind resource and land area to support a MWT farm. Since many of the other islands are mountainous, they may not necessarily possess this combination. The deployment of mWT10 throughout the Caribbean, however, could address any land area constraints. Extra-regional support could be solicited under the Clean Development Mechanisms (CDM) of the Kyoto Protocol. As Barbados is a non-Annex I country, it could benefit from investments from Annex I countries [26].

Wind farm advocates favour developments in the context of global warming abatement while not addressing the local concerns [27] of visual intrusion and the direct and indirect effects on wildlife. Issues of noise and electromagnetic interference are less of a real issue in modern machines. The "sensed visual impact" [28] is the basis for social opposition to large wind projects. All or part of the Lamberts East farm is expected to be visible from most points in St. Lucy and a few areas of the bordering parishes of St. Peter and St. Andrew. The use of anti-reflective coatings and low contrast colouring is currently used in order to make the machines more inconspicuous to humans, while potentially exacerbating the direct impacts on winged animals as they suffer from the reduced contrast of WTs with the background. The small rotor diameter of the mWT10 HAWT machines should mitigate the visual impacts over distance relative to the MWTs.

However, since the mWT10 units will likely spin at higher revolutions per minute (RPM) relative to the MWTs, they may be more noticeable [28]. Conversely, VAWTs could be less conspicuous due to the collinearity of the axis of rotation and pole. Moreover, since their blades rotate at the wind speed, their RPM should be lower relative to that of HAWTs.

Direct impacts on winged animals include injury and/or death due to collision or rotor wake. However many studies are inconclusive as to the number of injuries and deaths, due to infrequent site visits, scavenging and the possibility that injured birds move away from the site to recover from or succumb to their wounds. Many reports show low collision rates, except for those poorly sited farms in areas with large amounts of migration. It was indicated that birds local to the area display habituation insomuch as they learn to avoid the position of the farm [29]. Thus, the main concern may be for migratory birds that do not have the same memory advantage. Studies have shown that Barbados lies on a major migratory path for North American birds, though the island has few "native" species [9]. At 10 m AGL, mWT10 is well below migratory flight paths. Since VAWTs spin at wind speed, their blades move slower and are more visible to birds that may alight on overhead utility lines.

Indirect impacts, by virtue of habitat disturbance and loss, are usually not widely considered. Such losses arise in all phases of the existence of the farm, from construction, throughout operation to decommissioning. This can lead to all types of animals normally habituating nearby to move away. In the context of a small island, this may not lead to a large fauna deficiency, especially for land based animals.

However, in the same small island context, where the built environment is expanding, there could be cumulative effects of habitat loss from other projects as well as the proposed MWT farm. Conversely, mWT10 should not create additional habitat loss than that of the built environment in which it is being installed. Additionally, because it is distributed, it should not contribute to the disruptive effects that the centralized Lamberts East project might.

mWT10 is a distributed electricity from wind generation (DG) scheme, bringing the point of electrical generation closer to the point of consumption, akin to the proximity principle for waste. Other benefits of a DG configuration include scalability, flexibility and use of local resources. Traditional downsides, however, are lack of uniformity and consistency as well as management and information sharing hurdles [30]. The scalability of mWT10 provides a great advantage over Lamberts East. Specifically, there are sufficient implementation locations and expansion potential using the over 26,000 utility poles [1]. Moreover, expanding mWT10 using the currently installed pole infrastructure should not require planning approval whereas expanding the MWT farm would. Unlike Lamberts East, WTs mounted within the built environment will be subjected to complicated and widely varying wind conditions. Turbulence, leading to rapid wind speed and directional changes, and draughts, channelled by structures, could exceed the cut out velocity of a small HAWT while being in line with the features of VAWTs that do not have cut out speeds. It has been shown that lift driven VAWTs should outperform HAWTs in the (skewed) flow of air resulting from wind interacting with a roof [31].

In other islands, the turbulent effects and ensuing high speeds due to topographical features, such as mountains and valleys, should favour VAWT deployment in the same way as built environment effects. Geographical spread of wind turbines in the network is a very effective way of addressing short term output variability, as the fluctuations

become a smaller percentage of the rated plant capacity [8]. mWT10 can take advantage of a varied wind speed over a wide geographical area to offset potentially the low hub height. However for Lamberts East, low wind speed would result in low energy output due to collocation.

The lack of wind fuelled electricity generation in Barbados leaves either a top down or bottom up deployment approach. The BL&P is advocating the traditional centralized, large scale farm, which the preceding analyses show to be economically sound. An intermediate scheme could be a "neighbourhood farm," a cluster of two or three MWTs, local to the loads and scaled to the aggregate demand. Reducing machine size further leads to the use of small and micro machines on the order of a few kW, until the proposed mWT10 is eventually reached. As described, the top down approach is likely to receive the greatest social resistance because it is being introduced to a society where local confidence in, and experience with, the benefits of the farm may not outweigh the "clear" disadvantages. Conversely, the bottom up approach, starting with mWT10, proceeding to clusters and ultimately to large centralized farms may allow a degree of acclimatization to the idea of wind and its benefits, while using accumulating deployment time and increased local experience to address some of its negatives.

6. Conclusion

The BL&P proposed deployment of wind in Barbados is proposed chiefly to address GHG emissions, however, this paper asserts that it can also address issues of energy insecurity and sustainability. The use of micro WTs as an alternative to more conventional utility scale machines presents a number of technical issues, such as grid connection, but introduces benefits such as lower visual profile.

The BL&P outperforms mWT10 in all economic metrics, largely due to significantly lower relative installation and O&M costs. It is the only solution where a positive LCOE differential can be used for additional and diversified renewable deployment while maintaining the current conventional BDS$0.25 per kWh energy cost. The use of VAWTs is currently economically unjustified, however, it likely presents the best option for integration into the human and animal environment in Barbados and the other islands.

This analysis shows the potential of many small machines in a system as an option for large generation, competing favourably with the conventional, large wind projects. It gives the small wind industry targets to work towards on cost, reliability and performance. Furthermore, this paper has demonstrated that small wind can also excel in new areas, while avoiding many of the difficulties of large machines. The higher cost comes in light of some of these not (easily) quantified advantages. The subjective answer to whether each of these benefits in aggregate is worth the additional cost will determine whether a scheme such as mWT10 is realized.

7. Further work

Further work associated with mWT10 and renewable energy systems in Barbados includes:

- Measuring and evaluating energy outputs at potential mWT10 deployment points to assess scheme potential.
- Obtaining true pre-processing and post-operation ecological costs, including embodied energy during manufacture.
- Establishing the true value to the GoB of deferring the use of foreign currency for fuel purchase.
- Investigating the use of smaller clusters of MWTs dispersed within communities as an intermediate step between mWT10 and the Lamberts East farm.

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