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Wind resources and the levelized cost of wind generated electricity in the Caribbean islands of Trinidad and Tobago

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ABSTRACT

Affordable renewable energy is one key criterion for the long-term economic growth of Caribbean small island countries. The southernmost Caribbean islands, Trinidad and Tobago, have one of the lowest electricity rates in the region due to an indigenous source of hydrocarbons. In this study, technical and economic assessments were conducted to determine the levelized cost of electricity (LCOE) generation from the wind in these Caribbean islands. The assessments used extrapolations of 10 m level wind data sets for the two sites with long-term measurements (1989–2009), Crown Point and Piarco, and wind turbine characteristics of eight wind energy conversion systems ranging from 20 kW to 3050 kW. The annual average wind speeds at the 80 m height above ground were estimated to be 6.93 m/s and 5.86 m/s at Crown Point and Piarco, respectively, while corresponding estimates of wind power densities were 381 W m^{-2} and 296 W m^{-2}. The projected LCOEs for the large wind turbines, 1500 kW and greater, were less than the current subsidized residential tariff of US/$0.06/kWh. The Goldwind 1.5/87 1500 kW model produced the lowest LCOEs, US$0.031–US$0.039/kWh. The large wind turbines also have projected capacity factors in the range 0.22–0.39. Electricity generation from wind energy through the use of tall, large contemporary wind turbines could therefore be cost-competitive with electricity generation from hydrocarbons and is not prohibitively expensive as it is currently perceived. These results support government initiatives for large-scale wind farm developments as one avenue for diversifying the energy mix.

1. Introduction: cost of electricity in the Caribbean

Renewable energies, especially solar and wind, are expected to play a greater role in the energy mix of the southernmost islands of the Caribbean, Trinidad and Tobago. This may enable a more sustainable energy future for these islands as well as assist in reducing their emissions of carbon dioxide. Notwithstanding that the twin-island state of Trinidad and Tobago is a net exporter of hydrocarbons with an indigenous supply of natural gas and crude oil, and boasting one of the lowest subsidized residential tariffs in the region, second to Suriname [1], the Administration announced, in November 2015, an ambitious target of 10% renewable energy by 2021 [2]. There was an initial vision for large-scale implementation of wind technologies as outlined in the country's "Framework for the Development of a Renewable Energy Policy in Trinidad and Tobago" with a 5% power generation (60 MW) of bulk electricity generation to be supplied from wind by 2020 [3]. This was later superseded by a goal of 100 MW power generation [4] followed by the latest target of 10%. Current legislation in Trinidad and Tobago, introduced in 2010, offers incentives to home owners for the use of renewable energy technologies such as solar water heaters, photovoltaic cells and small wind turbines [5]. Wind energy was also proposed as a potential energy source for new housing development projects [6]. Although there is political will to enable large-scale wind energy projects, proposed policies and legislation for the implementation and use of renewable energy technologies will be guided by projections for the cost of electricity generation. However, while ambitious targets have been set, the cost of electricity generation from renewable energy technologies is considered to be prohibitively expensive in the Caribbean [7]. This situation is enhanced for Trinidad and Tobago because the indigenous supply of carbon based fuels enables immediate access to energy and the second lowest residential electricity tariff in the Caribbean region at US$0.06/kWh [1]. The

Abbreviations: IEC, International Electrotechnical Commission; kWh, kilowatt-hour; mmBtu, million British thermal unit; NREL, U.S. National Renewable Energy Laboratory; NCDC, U.S. National Climatic Data Center; O & M, operation and maintenance; pdf, probability density function; RMSE, root-mean-square-error; Tcf, trillion cubic feet; WECS, wind energy conversion systems; WMO, World Meteorological Organization; WPD, wind power density

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Nomenclature

c	Weibull scale parameter
c_a	Weibull scale parameter at anemometer's height
c_h	Weibull scale parameter at wind turbine's hub height
C_F	capacity factor of wind turbine
C_I	capital investments
f_v	frequency of wind speeds
$\overline{F}$	average empirical cumulative frequency
$\widehat{F}_i$	empirical cumulative frequency of the *i*th wind speed observation
$\widehat{F}_v$	predicted cumulative frequency of the *i*th wind speed observation using the Weibull pdf
I_d	discount rate
k	Weibull shape parameter
k_a	Weibull shape parameter at anemometer's height
k_h	Weibull shape parameter at wind turbine's hub height
m	annual variable cost for O & M as a fraction of the capital investment
n	number of observations/measurements
n_y	lifetime of wind turbine in years
P_D	wind power density derived from measured/extrapolated wind speeds
P_{DW}	wind power density estimate determined from the Weibull pdf fit
$P_{DW,h}$	wind power density estimate determined from the Weibull pdf fit at wind turbine's hub height
$P_{e,ave}$	mean power output of wind turbine
P_{eR}	wind turbine's rated power
R^2_{pp}	coefficient of determination for probability comparisons
R^2	coefficient of determination for linear regression model
v	wind speed
v_a	wind speed at anemometer's height
v_c	cut-in wind speed of wind turbine
v_f	cut-out wind speed of wind turbine
v_h	wind speed at wind turbine's hub height
v_r	rated wind speed of wind turbine
$\bar{v}$	average wind speed derived from measured/extrapolated wind speeds
$\bar{v}_W$	average wind speed predicted with the Weibull pdf
$\bar{v}_{W,h}$	average wind speed estimate at hub height determined from the Weibull pdf
z_a	anemometer's height
z_h	wind turbine's hub height
α	wind shear exponent
$\Gamma()$	Gamma function
ρ	air density
$\bar{\sigma}$	standard deviation in monthly wind speed derived from measured wind speeds
$\overline{\sigma_W}$	standard deviation in monthly wind speed determined from the Weibull pdf

perception of high cost of renewable energy is persistent due to a lack of technical and economic assessments based on the indigenous renewable energy sources. Thus, the determination of the levelized cost of electricity generation from wind for Trinidad and Tobago is the main focus of this work.

Wind generated electricity has shown to be more cost-competitive than solar energy in other regions [8] and is the renewable energy of choice for bulk electricity generation in the twin-island state [3]. While wind power is accepted to be a clean supply with minimal air pollution and greenhouse gas emissions, technical and economic benefits through projections of the energy outputs of wind turbines and the cost of such electrical energy generation could aid policy makers in modifying, developing, and adopting policies for the long-term sustainable development of Caribbean islands. The Caribbean Sustainable Energy Roadmap identifies the "lack of widespread calculation, understanding, and communication of renewable energy's cost effectiveness as a challenge for integrated energy planning" [7]. Only one type of study [9] has been done for Trinidad and Tobago recommending the amounts of subsidies to be removed for renewable energy to be competitive with natural gas generated electricity.

This therefore leads to our main aim which is to determine whether the levelized cost of electricity generation from wind is cost competitive with carbon based fuels for electricity generation in Trinidad and Tobago. To do this, we use available in-situ wind data sets for these Caribbean islands to project the energy outputs and the levelized cost of electricity generation for both small and large wind turbines. We first review the energy and economic status of Trinidad and Tobago and the cost of electricity generation from wind power as well as the need for a wind resource assessment in Section 2. Then, in Section 3, we describe the in-situ wind data used and outline the methods applied in performing a technical and economic assessment. We present the technical assessment in Section 4.1 and the levelized cost of electricity generation based on contemporary wind turbines that range from 20 kW to 3 MW in Section 4.2. Finally, we make our concluding statements based on the determined LCOEs for wind compared with the current subsidized tariff in Section 5.

2. Overview of energy, estimates of electricity generation from the wind, and previous wind resources assessments in Trinidad and Tobago

2.1. Energy and economic overview

The southernmost islands of the Caribbean, Trinidad and Tobago, have progressed at a slower rate than other Caribbean islands in diversifying into renewable energy due to an indigenous supply of natural gas and crude oil. Trinidad and Tobago is the only energy exporting *island* nation in the Caribbean and has enjoyed as much as 80% of export revenues from the petrochemical sector [10]. However, this economic dependence on the oil and natural gas sector makes the island state susceptible to the vagaries of the international pricing of crude oil and natural gas. Following the drastic drop in international crude oil prices at the end of 2014 into early 2015, Trinidad and Tobago has had to revise its 2015 annual budget [11,12]. The initial 2015 budget announced in September 2014 was prepared with revenues estimated from US$80 per barrel for oil and US$2.75 per mmBtu for natural gas [13]. The budget was subsequently revised in January 2015 with revenues based on US$45 per barrel oil and US $2.25 per mmBtu natural gas [11,12]. Later on in April 2016, a second consecutive mid-year review was necessary as oil and gas prices dropped to US$35 per barrel and US$2.00 per mmBtu, respectively. The resulting shortfalls of US$1.16 billion (in 2015) [11,12] to US $1.15 billion (in 2016) [14, TT$7.6 billion] are substantial for such small island economies, amounting to approximately 12.3% and 12.6% of the original projected revenues, TT$60.35 billion in 2015 [15] and TT$60.28 billion in 2016 [14].

In addition, proven natural gas reserves, currently at 13.1 Tcf, 0.2% of global reserves, have been declining slowly since 2005 [16]. The total natural gas reserves of 23.188 Tcf, at the current rate of consumption of 1.449 Tcf/year [17], is expected to last for 16 years. Compounded with decreasing natural gas reserves are concerns of increasing electricity demand; electricity consumption doubled from 3251 kWh/capita to 6629 kWh/capita between 1996 and 2012 [18]. The domestic