Assessing Solar Electricity Potential and Prospective Present Day Costs for a Low Latitude Caribbean Island: Trinidad

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Abstract

Presently, Trinidad and Tobago and many other Caribbean islands are faced with a challenge of integrating renewable energy into their energy sector. A key factor towards successful integration of any renewable energy resource in the electricity sector is through good economic prospects. In this study, the levelized cost of that energy (LCOE) output was determined by modeling utility scale solar photovoltaic systems in the absence of operational PV system data. An existing model of a utility scale solar system is adapted by considering energy loss factors at each stage of the electricity generation process. A range of LCOEs were determined by considering the ranges of the different losses in a PV system. The daily total in-plane insolation at Piarco for 2003 was used as input into an adapted model. The estimated energy was then applied to an economic model to calculate the LCOEs. For Piarco, the estimated annual performance ratios of PV systems were found to range between 56.6 % for maximum losses and 80.2 % for minimum losses and a performance ratio of 69.8% for standard losses. The standard loss model with a 3 % discount rate leads to LCOEs in the range US$0.07 - US$0.09 per kWh. These are promising results when considering incorporating solar energy into the energy mix of Trinidad and Tobago for electricity generation.

Keywords: solar energy, Trinidad and Tobago, PV system

1. Introduction

The Government of Trinidad and Tobago aims to ensure that by 2021, 10 % of power generation should come from renewable energy. However, currently, power generation is still 100 % fossil-fuel based. Trinidad and Tobago's economy is based on natural gas and crude oil production and they are the Caribbean's largest oil and natural gas producer (Ministry of Energy and Energy Industries of Trinidad and Tobago, 2017). In recent years, falling natural gas and crude oil production has resulted in a drop in revenue of TT$17.6 billion dollars, or 92 % in annual revenue (Government of the Republic of Trinidad and Tobago, 2016).

Solar energy is a clean source of energy which could contribute to electricity generation if implemented on a large scale basis and therefore, reduce the country's dependence on its fossil fuel resources. The first step in determining the feasibility of solar energy for electricity generation is the conduct of a national solar resource assessment. Such a complete solar resource assessment is currently unavailable for Trinidad and Tobago. To date, solar resource assessments have been limited mostly to the climatological assessment of solar radiation data, the development of models to predict monthly solar radiation (Smith, 1960; Stone, 1999; De Souza and Andrews, 2015; De Souza, 2018) and an assessment of "A unique approach for sustainable energy in Trinidad and Tobago" (Marzolf et al., 2015). A solar resource assessment provides reasonable and accurate projections of annual energy solar production at a prospective energy production site and therefore the performance of utility photovoltaics systems under varying climatic conditions (Makrides et al., 2010). It also considers the levelized costs of electricity (LCOE) generation as the financial aspects of a renewable energy project is key for further analyses and implementation.

To date, one study which has considered LCOEs for solar energy for Trinidad and Tobago evaluated the LCOE for solar generated electricity to be US$ 0.140 to US$0.288 per kWh at 2012 prices (Marzolf et al., 2015). They used meteorological software to determine the total solar irradiance and assumed a performance ratio (PR) more

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than 81.5 %. Performance ratios of photovoltaic systems range between 60 and 90 % (Dierauf et al., 2013). As such, in order to consider the economic feasibility of implementing utility scale PV systems in Trinidad and Tobago, the evaluation of the cost of electricity generation using a site specific performance ratio is of significance.

In the absence of operational utility PV systems, we are required to model the energy output of PV systems in order to estimate the LCOEs. This energy output is influenced by the PR of the PV system. The aim of this study is therefore to estimate the range of LCOEs for a site in Trinidad and Tobago using a range of possible losses and on site solar radiation data for the 2003 year. Nearby Caribbean islands are subjected to similar environmental constraints applied in this model and as such the approach applied here can also be used to supplement studies in those nearby islands.

2. PV System Model

Typical photovoltaic grid utility systems are made up of photovoltaic modules, inverters, mounting systems, transformers and grid connection (International Finance Corporation, 2015; Solargis, 2016).

In order to accurately estimate electricity that can be produced by a photovoltaic power plant, information on the solar resource, temperature conditions of the site, the layout and technical specifications of the power plant are required.

The performance ratio of the PV system, PR, as defined in the standard IEC 61724, is the quotient obtained by dividing the final yield of the PV system by the reference yield of the PV system and it represents the overall effect of the plant's losses on the rated array output (Khalid et al., 2016). E_{PV}, the net AC energy output of the system is found by:

$$E_{PV} = \frac{(PR)(P_r)(H_T)}{\mathrm{E_R}}$$ (Kymakis et al., 2009) (eq. 1)

where P_r is the peak power of the installed system under standard test conditions (STC) of 1000 W/m^2 solar irradiance and 25 °C cell temperature, H_T is the total in-plane solar irradiation and E_R is the array reference irradiance (1 kW/m^2).

Kymakis et al. (2009) defined the PR as the product of various losses:

$$PR = \frac{Y_F}{Y_R} = \eta_{deg}\eta_{temp}\eta_{soil}\eta_{net}\eta_{inv}\eta_{tran}\eta_{ppc}$$ (Kymakis et al., 2009) (eq. 2)

where Y_F is the final yield, Y_R is the reference yield, η_{deg}, η_{temp}, η_{soil}, η_{net}, η_{inv}, η_{tran} and η_{ppc} are the efficiencies due to module degradation, module temperature, module soiling, internal network losses, inverter losses, transformer losses and availability and grid connection losses respectively.

Similar to the definition used by Kymakis et al., (2009), the PR of the PV system is adapted to be representative of losses due to air mass (η_M), tilt (η_{tilt}), shading (η_{shad}), angular reflectivity (η_{AR}), soiling (η_{soil}), temperature (η_{temp}), inverter (η_{inv}), internal network (DC wiring and interconnection losses) (η_{net}), transformer (η_{tran}) and availability and grid connection (η_{ppc}). In this study, the PR is estimated using equation 3 and is then substituted in equation 1 to determine the net energy output E_{PV}.

$$PR = \eta_M\eta_{tilt}\eta_{shad}\eta_{AR}\eta_{soil}\eta_{temp}\eta_{inv}\eta_{net}\eta_{tran}\eta_{\mathrm{ppc}}$$ (eq. 3)

The monthly capacity factor (CF) of the PV system is found by:

$$CF = \frac{E_{PV}}{P_r \times No.\ of\ hours\ per\ month}$$ (eq. 4)

We account for losses in the various components such as the PV array, connecting wires, the inverter and the transformer. However, we modify the values of the loss factors to be representative for low-latitude regions, in particular, soiling, angular reflectivity, air mass and temperature characteristics.

Estimates of the potential losses due to specific factors such as air mass (Chegaar and Mialhe, 2008; Duffie and Beckman, 2006), shading (Duffie and Beckman, 2006; Sathyanarayana et al., 2015), angular reflectivity (Martı´n and Ruiz, 2005), soiling (Field et al., 2015; Mohammed and Hasan, 2012) and temperature on the module

(Skoplaki and Palyvos, 2009; Huld and Amillo, 2015) were made using site photovoltaic studies which considered losses specific to that location's latitude and climate. The performance loss due to inefficiencies in the internal network resistances (Kymakis et al., 2009; Kumar and Sudhakar, 2015), the inverter (Kymakis et al., 2009; Rehman et al., 2007; Kumar and Sudhakar, 2015), and the transformer (Kymakis et al., 2009, Kumar and Sudhakar, 2015) as well as losses incurred due to technical availability (Kymakis et al., 2009; Kumar and Sudhakar, 2015) were made using overall power system studies.

In this model, several loss factors are represented by a range of values rather than a single value where the model considers maximum, standard and minimum losses. The standard model will consider the normal or average expected losses.

The factors considered in the model for assessing the solar electricity potential are the efficiency of the module, air mass, tilt, shading, angular reflectivity, soiling, temperature, internal network efficiency, inverter efficiency, transformer efficiency and availability and grid connection losses. The suitable range of losses/ efficiency values was determined for each factor based on practical studies and experiences for low latitudes (Table 1).

Tab. 1: Range of derate factors considered

Derate Factors	**Partial losses due to individual factors (%)**			**References**
	Min	**Max**	**Standard**	
Efficiency of PV module	80.00	88.00	84.00	International Renewable Energy Agency (2012), International Finance Corporation World Bank Group (2012), Smets et al. (2015)
Effect of air mass	0.00	1.00	1.00	The air mass for Trinidad was calculated. Chegaar and Mialhe (2008)
Effect of tilt angle of module	0.00	0.00	0.00	The model considers a horizontal module.
Effect of shading	1.00	6.00	2.50	Duffie and Beckman (2006) Sathyanarayana et al. (2015)
Effect of angular reflectivity	3.00	4.00	3.50	Martı´n and Ruiz (2005)
Effect of soiling	1.00	7.00	1.50	Trinidad has exposure to Sahara dust. Duffie and Beckman (2006) Mohammed and Hasan (2012) Kimber et al. (2006) Kymakis et al. (2009)
Effect of temperature	8.50	15.00	10.00	Huld and Amillo (2015) Ariza Taba et al. (2016) Parretta et al. (1998) Vasisht et al. (2016)
Effect of internal network losses	3.00	6.00	5.00	Kymakis et al. (2009) Kumar and Sudhakar (2015)
Effect of inverter losses	2.00	8.00	5.00	Kymakis et al. (2009) Rehman et al. (2007)

				Kumar and Sudhakar (2015)
Effect of transformer losses	1.00	2.50	2.00	Kymakis et al. (2009) Shukla et al. (2016) Kumar and Sudhakar (2015)
Effect of availability and grid connection losses	2.00	5.00	4.50	Kymakis et al. (2009) Kumar and Sudhakar (2015)

2.1 Description of the PV System

This study focused on crystalline photovoltaic systems as crystalline systems are today the most widely used (Buchla et al., 2015). The model considers a horizontal module and therefore the effect due to tilt is not considered. It was further assumed that the photovoltaic system in this energy model is to be set up in flat terrain, isolated from the shading of large vegetation and buildings.

3. Study Area and Data

3.1 Study Area

Trinidad and Tobago are the most southern islands of the Caribbean archipelago (Gov.tt 2017). The global solar radiation data for this study were obtained for Piarco, Trinidad, for the period 2000 to 2010 from the Trinidad and Tobago Meteorological Office. This station is a World Meteorological Organization (WMO) station.

Trinidad and Tobago has a dry and a wet season. The dry season spans the months of January to May while the wet season extends from June to December. The climate experienced during the dry season is a tropical maritime climate while the wet season experiences a modified moist equatorial climate. The mean maximum and minimum temperatures (1971-2000) in Trinidad are 31.3 °C and 22.7 °C respectively (Trinidad and Tobago Meteorological Service 2017). Piarco has an average annual wind speed of 2.88 m/s at the 10 m height (Chadee, 2015). The annual average of daily solar radiation for Piarco was calculated to be 4.41 kWh/m^2.

3.2 Data Quality Control

The daily global radiation data for Piarco, Trinidad were obtained for the period 2000 to 2010. Each data value in the daily data set was checked for instances of missing days, negative values and zero values. No missing daily totals are permitted in calculating the monthly global radiation. Also, no missing monthly normals are permitted if an annual normal is to be calculated. Checks for thresholds were also conducted. Daily data values were checked against the upper limit of each month and below the lower limit for each month as defined by WMO (1987). In low latitude regions throughout the year, the minimum daily values average was about 0.3 to 0.4 MJ/m^2 (WMO 1987). All daily averages were checked against a lower threshold of 0.4 MJ/m^2. After subjecting the data to all the quality control steps outlined, only one valid year of data (2003) was obtained.

3.3 Site Specific Solar Insolation Characteristics

The dataset consisted of the daily total in-plane insolation for 2003 at Piarco, Trinidad. In 2003, the daily total in plane insolation range was 0.85 - 6.15 kWh/m^2 with a daily average of 4.41 kWh/m^2. The monthly total in-plane insolation ranged from a minimum value of 109.48 kWh/m^2 in November 2003 to a maximum value of 158.64 kWh/m^2 in March 2003 (Figure 1). The dry season had a higher monthly average total in-plane insolation for 2003 of 145.94 kWh/m^2 as compared to the wet season with 125.80 kWh/m^2.

The annual total in plane insolation for 2003 was found to be 1610.27 kWh/m^2. This value was measured at Piarco and is used as a representative value for Trinidad. This observed value is smaller than the value of the total insolation 1761 kWh/m^2 used by Marzolf et al. (2015) who used meteorological software to estimate the total in-plane insolation at 15 % tilted surface at Crown Point, Tobago.

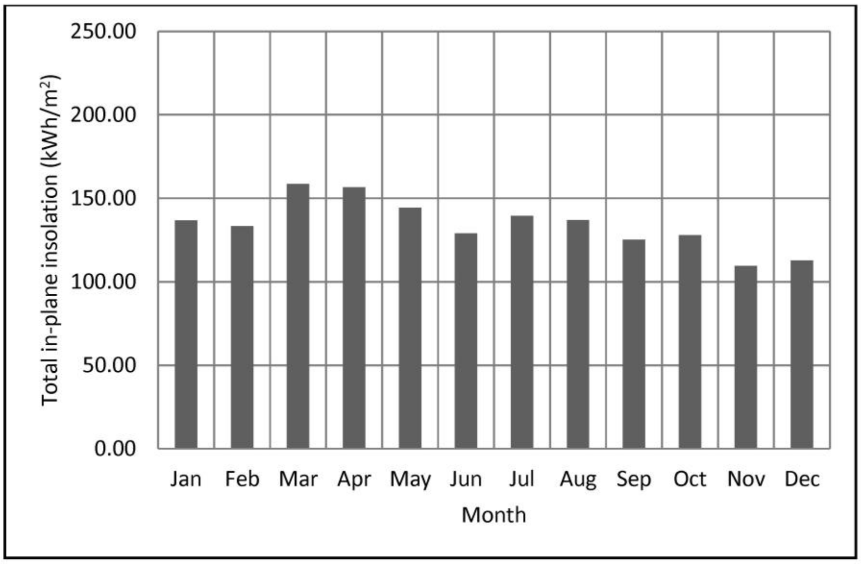

Fig. 1: Monthly total in-plane insolation for 2003

4. Energy Analysis

4.1 Annual Energy Analysis

The model resulted in a range of annual performance ratios between 56.6 % and 80.2 % with a standard modelled value of 69.8 % and capacity ratios between 10.4 % and 14.8 % with a standard modelled value with 12.8 %. This resulted in annual electricity generating capacities of 4555 MWh to 6459 MWh for a 5 MW system, 9109 MWh to 12920 MWh for a 10 MW system, 45550 MWh to 64590 MWh for a 50 MW system and 91090 MWh to 129200 MWh, in their first year of operation.

4.2 Estimated Monthly Capacity Factors

For the PV systems considered, the monthly capacity factors were estimated to range from 10.6 % to 15.2 %. Overall, all systems produce the maximum amount of electricity during March to May as these months have the highest total in-plane insolation. The minimum electricity generating months are November and December as they have the lowest total in-plane insolation of the year.

4.3 Annual Energy Sensitivity Analysis

Table 2 shows how the performance ratio and capacity factor may be influenced by the variation in estimated losses of individual factors considered in the model.

Tab. 2: Properties of the photovoltaic system within the considered range of losses

Overall Model Losses	Performance Ratio (%)	PR – standard PR (%)	Capacity Factor (%)	CF – standard CF (%)
Minimum	80.2	10.5	14.8	1.9
Standard	69.8	0.00	12.8	0.00
Maximum	56.6	-13.2	10.4	-2.4

5. Economic Analysis

An accurate valuation of the cost of solar energy generation is required for the development and integration of photovoltaic technologies. The levelized cost of electricity (LCOE) is a standard technique used in energy generation projections and technology assessments (Foster et al., 2014) and is frequently used when comparing electricity generation technologies or considering grid parities for emerging technologies (Hernández-Moro and Martínez-Duart, 2013; Branker et al., 2011; IRENA, 2012). The LCOE is the net present value of the total life cycle cost of the project per quantity of energy produced over the system life (Cambell, 2008).

In this study a constant dollar, no-tax, LCOE (Short et al., 1995) is considered. It is defined by the following equations:

$$LCOE = \frac{TLCC}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}} \quad \text{(eq. 5)}$$

$$TLCC = I + PVOM \quad \text{(eq. 6)}$$

$$PVOM = \sum_{N=1}^{n} \frac{O\&M_n}{(1+d)^n} \quad \text{(eq. 7)}$$

where $LCOE$ is the levelized cost of electricity, $TLCC$ is the total life cycle cost, Q_n is the energy output or energy saved in year n, d is the discount rate, N is the analysis period, I is the initial investment, $PVOM$ is the present value operating, maintenance and fuel expenses and $O\&M$ is the annual operating, maintenance and fuel expenses.

This model considers the application of no taxes and is applied to non-profit and Government ventures (Short et al., 1995). The model is simplistic given that this is a baseline study. It is widely used as a first order measure to compare power generating technologies (IRENA, 2017). In addition, it is transparent and easy to understand (IRENA, 2017).

Generic cost data (Fu et al., 2017), shown in Table 3, was used to model the total life cycle cost of the photovoltaic systems at different discount rates and lifetime/analysis periods. Good quality photovoltaic modules have a degradation rate of 0.75 % per year (Fu et al., 2017) and as such this study will be done for a 25-year lifetime with a degradation rate of 0.75 %.

Tab. 3: The Input Cost Data (Fu et al., 2017)

Capacity (MW)	Installed Cost (USD/ kW)	Operations and Maintenance Cost per Annum (USD/ kW annum)
5	1381.52	15.40
10	1264.02	15.40
50	1119.38	15.40
100	1029.21	15.40

The LCOE was determined at different discount rates; 3 %, 4.75 %, 5 %, 7 % 10 %, 15 %. Marzolf et al. (2015) used 4.75 % in that study as given by the Central Bank of Trinidad and Tobago on December 6th, 2012.

IRENA (2015) and IRENA (2017) recommends that a 10 % discount rate be applied to non-OECD countries such as Trinidad and Tobago. Wittenstein and Rothwell (2015) states that a real discount rate of 3 % should be used by government-owned utilities in countries with good bond ratings or ones with stable rate-of-return regulation and fuel price increase allowances while it is recommended that countries with government-owned utilities with poor bond ratings use a higher discount rate. As such, a minimum 3 % discount rate is considered in this analysis. Wittenstein and Rothwell (2015) recommends that a 7 % real discount rate can be considered as the rate available to an investor with a low risk of default in a stable environment or to private investors in a low-risk technological option in a favourable market environment. The 10 % real discount rate is recommended for investments with considerably larger financial, technological and price risks (Wittenstein and Rothwell, 2015). A maximum 15 % discount rate is considered for an extreme case of high technological and price risks.

The variation is the LCOE is shown in Table 4. It was found that the LCOE may range between USD 0.06 to 0.26 depending on the size of the system and the discount rate considered. The LCOE for the standard loss energy model ranged from USD 0.07 to 0.21. The variation in cost according to system size was small, as all systems showed a minimum LCOE of USD 0.06 to 0.08 (at a 3 % discount rate) and a maximum LCOE of USD 0.20 to 0.26 (at a 15 % discount rate). The LCOE for the minimum loss model and the maximum loss model are 87 % and 123 % compared to the standard model respectively.

Tab. 4: LCOE of standard model considering the overall modelled losses (maximum, standard and minimum) at different discount rates

Discount Rate (%)	**LCOE$_{MINIMUM\ LOSSES}$ (USD)**				**LCOE$_{STANDARD\ LOSSES}$ (USD)**				**LCOE$_{MAXIMUM\ LOSSES}$ (USD)**			
	5 MW	**10 MW**	**50 MW**	**100 MW**	**5 MW**	**10 MW**	**50 MW**	**100 MW**	**5 MW**	**10 MW**	**50 MW**	**100 MW**
3	0.08	0.07	0.07	0.06	0.09	0.08	0.08	0.07	0.11	0.10	0.09	0.09
4.75	0.09	0.08	0.08	0.07	0.10	0.10	0.09	0.08	0.13	0.12	0.11	0.10
5	0.09	0.09	0.08	0.07	0.11	0.10	0.09	0.08	0.13	0.12	0.11	0.10
7	0.11	0.10	0.09	0.09	0.13	0.12	0.11	0.10	0.16	0.14	0.13	0.12
10	0.14	0.13	0.11	0.11	0.16	0.15	0.13	0.12	0.19	0.18	0.16	0.15
15	0.19	0.17	0.15	0.14	0.21	0.20	0.18	0.16	0.26	0.24	0.22	0.20

6. Discussion

Utility sized PV systems were modelled for one site in Trinidad and Tobago using system losses and existing on-site global solar radiation data collected in 2003. Annual performance ratios were found to range between 56.6 % for minimal losses and 80.2 % for maximum losses and a performance ratio of 69.8 % for standard losses. Only one previous study, Marzolf et al. (2015), assumed a performance ratio for a photovoltaic system in Trinidad and Tobago to be 81.5 %. They assumed that typical systems have performance ratios between 80 and 90 %. This value is larger than the 69.8 % performance ratio found in this study by using standard losses. The estimated performance ratio of 69.8 % is within the typical range of performance ratios of photovoltaic systems, 60 % to 90 %, as assessed by NREL (Dierauf et al., 2013). The average performance ratio found is smaller than those found for operating PV systems in various countries such as Malaysia (70.88 % and 77.28 %) (Humada et al., 2017; Farhoodnea et al., 2015), India (85 % - 86.12 %) (Vasisht et al., 2016; Kumar and Sudhakar, 2013) and South Africa (84 %) (Okello et al., 2015).

The standard loss model leads to LCOEs in the range US$0.08 - US$0.10 per kWh at 4.75% discount rate. Marzolf et al. (2015) used the same discount rate and estimated LCOEs to be US$0.14 – US$0.29 per kWh. The lower LCOEs of this study may be attributed to the global reduction in capital costs of solar PV plants. Marzolf et al. (2015) had used costs in 2012 while we used 2017 costs in this study.

Lower discount rates could make solar PV plants in Trinidad and Tobago competitive with current electricity tariffs. At 3 % discount rate and maximum losses, LCOEs range from US$0.06 - US$0.11 per kWh. The upper end of the range is approximately twice the subsidized electricity tariff in Trinidad and Tobago (US$0.040 - US$0.054 per kWh) (T&TEC, 2018; Central Bank of Trinidad and Tobago, 2018). Given the economic climate in Trinidad and Tobago, it is expected that electricity rates are due for an increase. This could make solar PV comparable with new electricity tariffs. LCOEs of US$0.11 per kWh for solar PV in Trinidad is also less than the residential electricity tariffs in other Caribbean islands who import most of their energy and contain a renewable energy component. Jamaica, Barbados and St Kitts and Nevis had residential electricity rates of US$0.32, $0.28 and $0.23 to $0.26 respectively in 2013 (US Department of Energy, 2017).

Based on the analyses of this study, we find that solar PV in Trinidad could be cost competitive for electricity generation under low discount rates. This pre-feasibility analysis provides a foundation for proceeding with more detailed solar PV analyses in Trinidad and Tobago via assessing actual PV system performance and validating the estimated LCOEs.

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