Design and Optimization of a Renewable Energy System for an Industrial Building in Trinidad and Tobago

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Received: 29.03.2023 Accepted:04.05.2023

Abstract- Development of efficient, reliable, and cost-effective renewable technologies is lagging in Trinidad and Tobago (TT) and data required for implementation is limited. This investigation will help in bridging this gap through the design and optimization of different renewable energy (RE) systems for a small industrial business in the city of San Fernando in Trinidad and Tobago. Different RE energy systems (wind, PV, and hybrid) are designed, simulated, and optimized using the Homer Pro Software with a least cost objective function using resource availability data from the National Renewable Energy Laboratory (NREL). In the base case scenario, with the subsidized electricity cost of US$ 0.06/kWh, the site was found to use approximately 21,535 kWh at an annual cost of US$ 1,292 and associated CO_2 emissions of 13,610 kg. At this present subsidized cost of electricity and without grid sellback, only the wind based RE system was economical, with a cost of energy (COE) of US$ 0.0443/kWh and RE penetration of 82.6% however, the system was not technically feasible due to space limitations. Without grid sellback, the solar PV system was economical at a much higher COE of US$ 0.339/kWh but with a lower RE penetration of 44.2% indicating that there would be no financial benefit to adopt a solar PV system at the site at both the subsidized rate and estimated unsubsidized rate of electricity ($US 0.12/kWh). When grid sell back is considered, the PV system is economical at a much lower COE of US$ 0.252/kWh (with a grid price of US$ 0.33/kWh at a sellback rate of US$ 0.22/kWh) with associated higher RE penetration of 62.2%.

Keywords- Renewable Energy; Wind Energy; Solar Photovoltaic; Homer Pro.

1. Introduction

Greenhouse gas (GHG) emissions have risen to unprecedented levels due to factors such population growth, industrialization, and pollution, which have contributed significantly to the phenomena that is the greenhouse effect, leading to detrimental consequences on the environmental landscape as a result of the intensification of global temperatures and rising sea levels [1]. Based on population size, Small Island Developing States (SIDS) have been responsible for insignificant levels of greenhouse gases, however Trinidad & Tobago (TT) is ranked fourth based on annual CO_2 emissions per capita [2]. TT is an oil and gas-based economy with an abundant but steadily decreasing supply of petroleum hydrocarbons [3]. Like many other countries that rely economically on their oil and gas sector, there is a trust to reduce Greenhouse Gas (GHG) emissions related to energy generation [4]. Being a SIDS, climate change will greatly impact human health, agriculture, coastal zones, and tourism [5]. TT is signatory to the United Nations (UN) Paris Agreement and due to worldwide global environmental awareness and the decrease in fossil fuel resources, there is a definite need for energy diversification for the reduction of pollution and climate impacts related to the use of fossil fuels [6]. Globally, there is much emphasis on research and development of efficient, reliable, and cost-effective renewable technologies which are less susceptible to market shocks with improved resilience and energy security [7-16]. The increased usage of modern solar technology and solar PVs have been attributed to increased performance, efficiency, and reliability and a gradual decrease in cost of the technology [17]. The recent development of smart grid technologies has resulted in many countries integrating RE by as much as 20%, whilst increasing energy efficiency by 20% and reducing carbon emissions by 20% [18]. Although previous studies have identified wind and solar energy as obvious choices for renewable energy sources, TT is lagging in terms of research and development activity around RE systems and there is limited information in the literature [19]. Additionally, electricity produced in TT is highly subsidized which presents another barrier to the use of RE. As observed by Siswantoro and Ridho in a case study of electricity usage in Indonesia, subsidized fuel prices present a challenge to making RE including solar power locally viable [20]. Oman for example has increased reliance on RE sources of energy as they have experienced significant industrial and population growth which have placed pressure on the power infrastructure which is fueled by their limited oil and gas reserves [21]. The absence of grid interconnectivity, as well as the lack of skilled and technically qualified renewable energy practitioners, are additional factors limiting the transition to cleaner energy sources [22].

The use of the computer-based modelling technique has been a highly successful research and development tool for the design and evaluation of renewable energy systems [23-31]. Ahammed [25] and Yasin & Alsayed [26] identified that Hybrid Optimization of Multiple Electric Renewables (HOMER) or HOMER Pro software, developed by the National Renewable Energy Laboratory (NREL), is one of the more popular modelling software used for hybrid system development [27]. The software was used to determine and evaluate the different options available for solar and wind systems, and to evaluate the feasibility of a solar-wind hybrid renewable energy system based on solar radiation and the wind energy potential available at specific locations. This study identified the use of levelized cost of energy (LCOE) and net present cost (NPC) as the criteria for system evaluation. Research conducted by Yasin & Alsayed [26] supported the conclusions of the study by Ahammed [25] and utilized the HOMER Pro software for system optimization, sensitivity analysis and feasibility studies based on a life cycle cost by calculating Net Present Value (NPV) and LCOE. Yasin and Alsayed [26] also demonstrated that where renewable energy sources are intermittent and cannot be utilized alone to fulfil the load demands, configurations including energy storage, diesel generators, and grid electricity may be required.

This paper will look at the design and optimization of a suitable renewable energy system appropriate for small industrial business in the City of San Fernando in TT. After completion of an American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Level 1 Energy Audit of the building and the development of the building's load profile, RE systems will be designed and optimized using Homer Pro. Evaluations will be conducted by comparing the economics of the existing grid system with a standalone RE system, the impact of subsidized and unsubsidized cost of electricity and diesel costs, system costs, load increases, the influence of grid sellback prices, and the reduction on CO_2 emissions that can be achieved. This study will bridge the information gap by providing data driven and scientific evidence required to facilitate the use of renewable energy systems in TT. The methodology will now be described followed by the presentation and discussion of the results before the conclusion.

2. Methodology

The sequence of steps involved in the simulation and evaluation of an industrial building is described in the methodology flow chart in Figure 1.

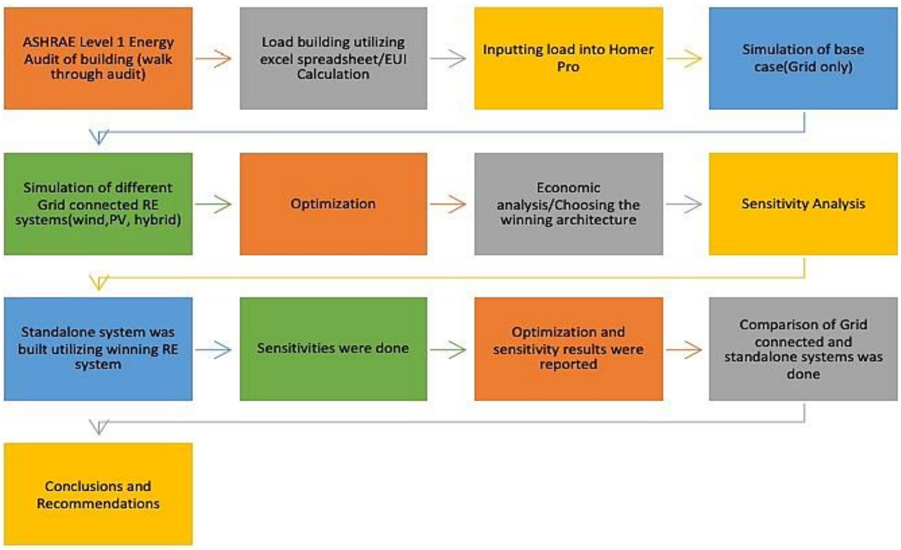

Figure 1. Methodology Flow Chart.

ASHRAE Level 1 Energy Audit and Preliminary Review of Energy Use

A Level 1 energy audit was conducted at the industrial building in San Fernando. Bi-monthly electricity bills were collected to account for patterns of energy. A base load profile was built in an excel spreadsheet using the following relationships.

- Monthly kW = (Monthly kWh)/ (days in month X hours in day X load factor)
- For commercial Bills, assumed a load factor of 0.75

Energy Utilization Index (EUI) was then calculated using the following relationship.

$$EUI = \frac{annual\ energy\ use}{square\ footage} \quad (1)$$

The results obtained from the EUI, and base energy load was then used to benchmark the data against energy use of similar buildings and can be used for identifying energy saving opportunities.

Simulations using Homer Pro Software

Simulations using Homer Pro Software were conducted as outlined by Yasin & Alsayed [26]. The load profile was uploaded into the Homer Pro software, this served as the base load for all the models built. A base model was constructed which consisted of the simplest model. The grid was utilized alone for the base case. Other models were then built on the base case utilizing different combinations such as Grid and Photovoltaic panels (PV panels), Grid and wind turbines as well as grid, wind turbine and PV panels (hybrid). The component specifications were kept constant allowing the system design to be the only variable. This was done for both grid tied and off grid scenarios. Some of the economic indicators utilized for the determination of the winning architectures for both the off grid and on grid scenarios were chosen based on net present cost, cost of energy (COE), capital cost, operating cost, fuel cost, CO_2 emissions, and renewable fraction. Homer displayed the list of configurations sorted by net present cost to quickly locate the least costly system. Sensitivity analysis of the optimized winning architectures for the off-grid and on-grid systems was then done to determine the factors that had the greatest impact on the system design and operation. Variables used for the sensitivity analysis included subsidized, unsubsidized, and international fuel prices (for diesel generator used in the standalone system), subsidized and unsubsidized cost of electricity, PV costs, and variability of the load. Key inputs used in the simulation include:

- Weather data – Resource information such as wind speed and temperature data were obtained from the National Aeronautics and Space Administration (NASA) database according to the location of the facility mapped in the HOMER Pro software.
- Fuel cost – Current diesel subsidized cost of US$ 0.50/L in Trinidad and Tobago and unsubsidized rate of US$ 0.78/L at an oil price of US$ 100/barrel [32].
- Electricity Cost.

a) Subsidized electricity rate - US$ 0.06/kWh (derived from the utility bills from the commercial building of interest - for a commercial building in Trinidad this is currently TT$ 41.50 per kWh/ US$ 0.06 per kWh)

b) Unsubsidized cost was estimated to be US$ 0.13/kWh for Trinidad and Tobago. Since natural gas prices were unavailable, it was estimated based on the trend of gasoline as they both have similar trends based on the fuel subsidy as shown in Table 1 and Figure 2. The average rate for the Caribbean was US$ 0.33/kWh [33].

Table 1. Cost of electricity and gasoline prices [34]. The data in blue was estimated.

Date	Cost of electricity	Price of gasoline
May-15	0.08	0.5
Nov-20	0.06	0.3
Oct-22	0.105	0.75
Jan-23	0.126	0.96
Jan-24	0.127	1.03

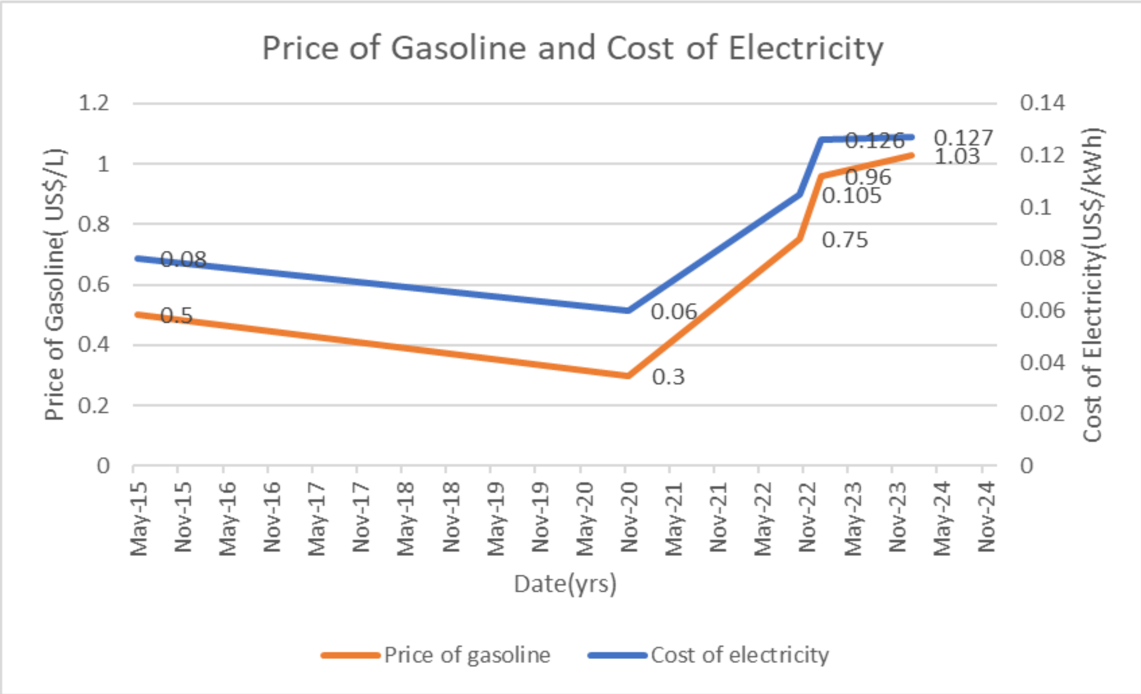

Figure 2. Graph of trend of cost of electricity and price of gasoline.

- Component specifications such as operating and maintenance costs, capital costs, lifespan, PV panel efficiency.

  a. Capital expenditures/Lifetime

  - PV Panels - Cost for generic flat plate PV system. US$ 1,714 (cost for a 1kW system, this was calculated based on the TT$ cost for a 5kW system) [35] – lifetime 25 years
  - Wind Turbine – US$ 13,000 for 10kW turbine (calculated from the cost of 1MW system being US$ 1.3MM) with a lifetime of 20 years [36]
  - Batteries – US$ 271 each (15000 hrs.) [37]
  - Diesel Generator – US$ 4,485 for 10kW capacity [38]
  - Power Converter - $ 1000/kW (15 years lifetime) [26]

  b. Operational and maintenance expenditures

  - PV Panels –US$ 150/kW/yr. [39]
  - Wind Turbine – US$ 260/kW/yr. per turbine, this was calculated as being 2% of original cost [40]
  - Batteries – US$ 10/yr. [26]
  - Diesel generator – US$ 0.03/h [12]
  - Converter – US$ 4/yr. [26]

  c. Emission rate – 700g/kWh carbon factor from electricity generation in Trinidad and Tobago [19]

3. Results and Discussion

Energy Profiles

The base energy load profile was developed based on the calculated energy usage values. Figure 3 shows the typical day load profile for the building which shows heaviest usage between 8:00 am to 12:00 pm and 1:00 pm to 4:00 pm. Figure 4 shows the monthly energy usage pattern identifying the peak load occurring in March and April. The yearly profile seen in Figure 5 was generated by introducing random variability into the load, with a day-to-day variability of 9% and timestep variability of 5 % (to account for any dips and surges as is seen in reality). The annual Average kWh/day was also scaled to account for the peak load of the building which was 9.37 kW.

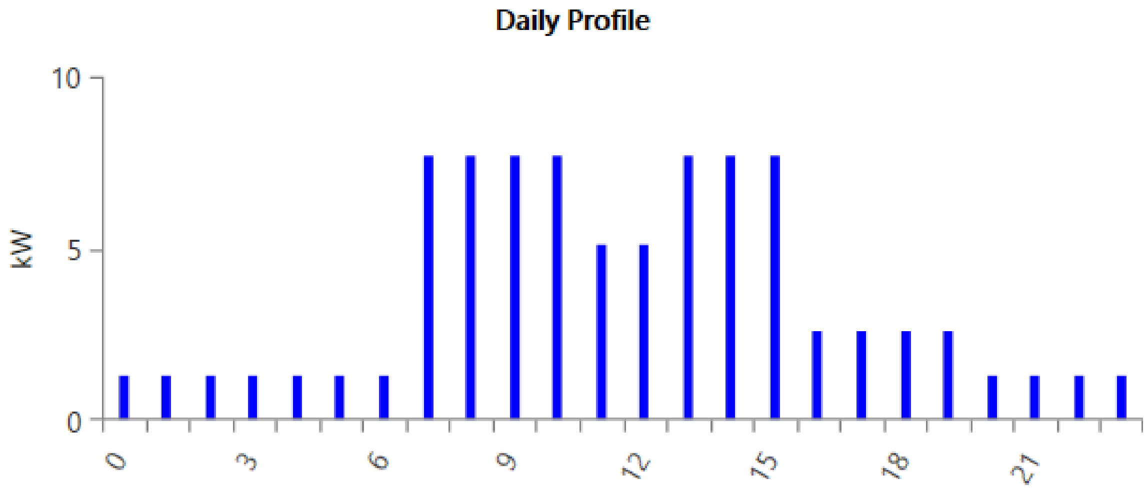

Figure 3. Daily profile showing the general day shape.

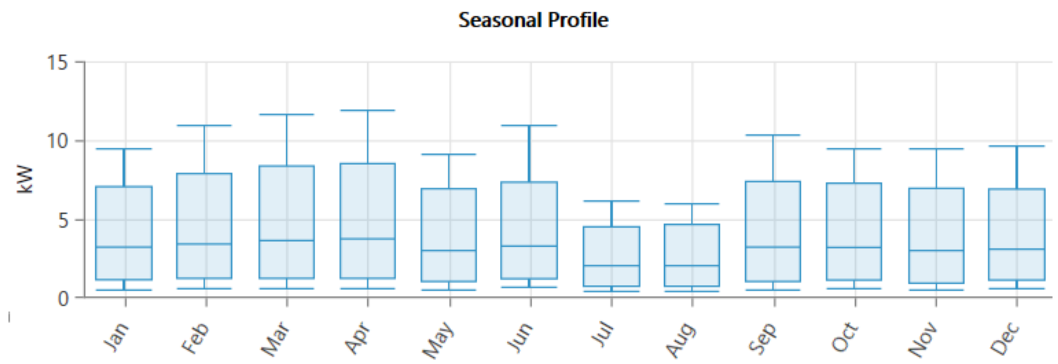

Figure 4. Seasonal Load profile.

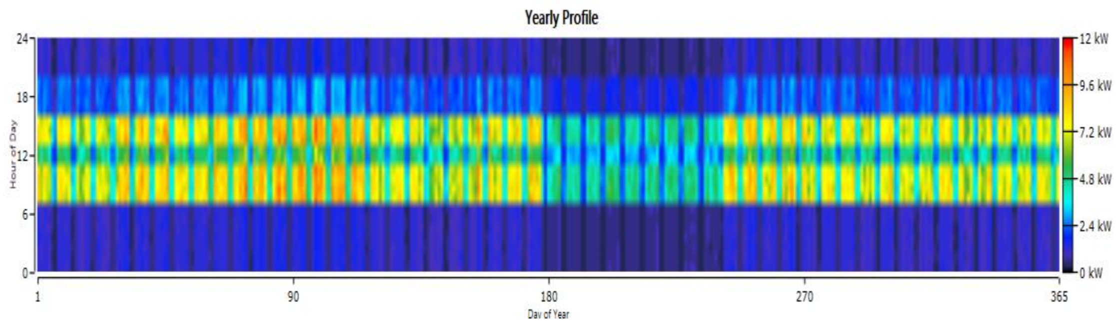

Figure 5. Yearly Load Profile.

Grid Connected Cases

Base Case – Grid Only

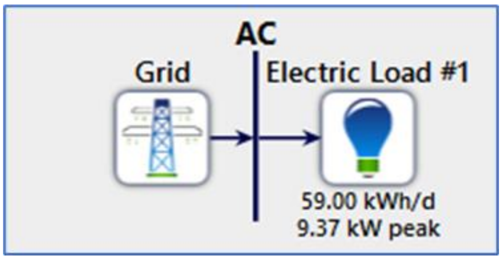

Figure 6. Base Case system - Grid Only.

The base case of the grid only scenario as shown in Figure 6, was simulated using the current cost of electricity (TT$ 41.50/kWh or US$ 0.06/kWh for a commercial building) obtained from the kwh consumption cost from the utility bills for the building. The results for the grid only base case optimized scenario are shown in Table 2.

Table 2. Base Case Optimization results (Grid only).

Parameter	Grid only
NPC ($US)	16,704
COE ($US)	0.06
Operating Cost($US/yr)	1,292
Initial Capital Cost ($US)	0
O&M ($US/yr)	1,292
Ren Frac (%)	0
Electricity Produced (kWh/yr)	21,535
Excess Electricity (%)	0
CO_2 (kg/yr)	13,610

The results demonstrated that the operating cost was US$ 1,292 per year and there is no renewable energy being utilized or recommended at this low cost of electricity. The CO_2 generated is this scenario was found to be 13, 610 kg per year.

Renewable Energy Cases

Renewable Energy Case 1- Grid with PV

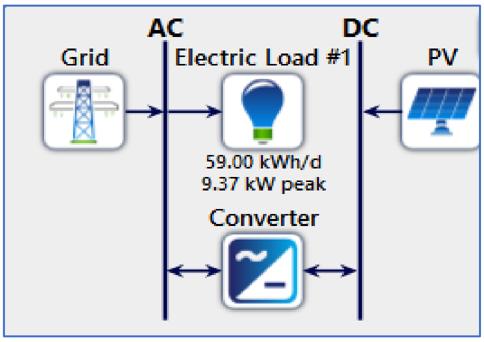

Figure 7. RE system, Grid and PV only

In this scenario, a 1kW Generic flat plate PV system with a converter was added to the model created in the previous grid only base case and this configuration is shown in Figure 7. In TT, a 5kW system costs approximately TT$ 60,000 (US$ 8, 571) with an average cost for a 1kW PV system being approximately TT$ 12,000 (US$ 1,714) with operations and maintenance cost being US$ 150 annually [35]. The converter cost used was US$ 1,000 with an associated operations and maintenance cost of US$ 4/yr. The optimization results show that the best system from an economic perspective remained the grid only option due to the low cost of electricity and lower NPC (Table 3). The results did indicate that a 20kW PV system with a 5kW converter was associated with a COE at US$ 0.271/kWh, a renewable fraction penetration (RP) of 65.7% and a CO_2 production of 5,362 kg/yr. Similarly, a larger PV system afforded more RP (90.7%) and lower CO_2 emissions, but at much higher COE (US$ 0.351/kWh) and NPC. These other PV scenarios also produced substantial amounts of excess electricity which can be sold back to the grid resulting in improved economic feasibility of these scenarios.

Table 3. Grid with PV and Converter Optimization Results.

Parameter	Grid only	Grid and PV system (>50% RP)	Grid and PV system (Largest System)
NPC ($US)	16,704	86,624	244,016
COE ($US)	0.06	0.271	0.351
Operating Cost ($US /yr)	1,292	3,662	9,760
Initial Capital Cost ($US)	0	39,280	117,840
O&M ($US /yr)	1,292	3,529	9,361
Ren Frac (%)	0	65.7%	90.7%
Electricity Produced (kWh/yr)	21,535	37,833	93,057
Excess Electricity (%)	0	32.3%	39.4
CO_2 (kg/yr)	13,610	5, 362	3,167

Renewable Energy Case 2- Grid with Wind Turbine.

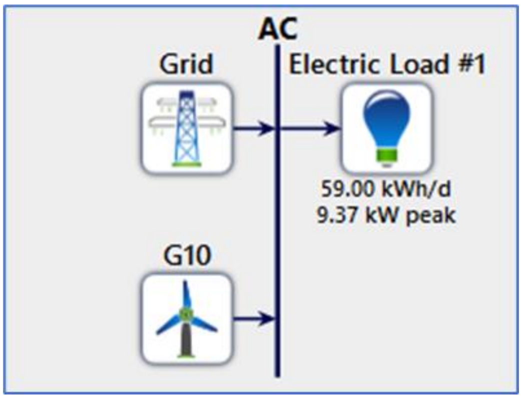

Figure 8. Grid and Wind Turbine only.

The scenario utilizing a Grid in conjunction with a 10kW Generic Wind Turbine, as shown in Figure 8, was simulated. The capital cost used for the wind turbine was US$ 13,000 with operations and maintenance cost calculated to be US$ 260 (2% of capital cost based on international costs). The results obtained are shown in Table 4 and demonstrates that if the grid and wind system is utilized, there will be an 82.6% penetration of renewables. This option is feasible, as the cost of energy calculated by Homer pro was lower in comparison to the grid only option. The wind system generated CO_2 emissions of 4,569 kg/yr. significantly lower than the 13, 610 kg/yr. for the grid only base case option (66% reduction). The downside associated with the wind turbine system is its high initial capital cost whereas the grid had a capital cost of US$ 0.00. For this reason, economic feasibility can only be enhanced in TT if financial incentives and tax rebates are implemented to facilitate cheaper importation costs.

Table 4. Grid, wind, and converter optimization results.

Parameter	Grid only	Wind Turbine and Grid
NPC ($US)	16,704	12596
COE ($US)	0.06	0.0443
Operating Cost($US/yr)	1,292	833.66
Initial Capital Cost ($US)	0	13,000
O&M ($US /yr)	1,292	693.74
Ren Frac (%)	0	82.6
Electricity Produced (kWh/yr)	21,535	41,502
Excess Electricity (%)	0	0
CO_2 (kg/yr)	13,610	4,569

Renewable Energy Case 3 - Grid with Wind, PV, and Converter (Hybrid Model)

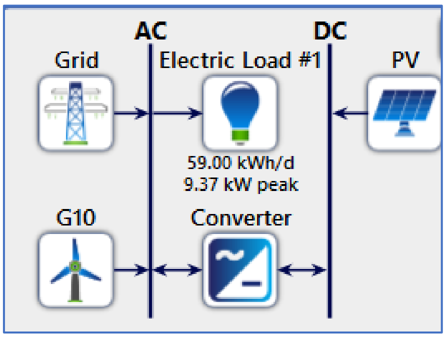

Figure 9. Grid, wind, PV, and converter (Hybrid System).

A hybrid model consisting of grid, a wind turbine with PV and Converter as shown in Figure 9, was optimized and the results are shown in Table 5. The results show that the 10kW wind turbine with grid was the most optimal system to handle the load requirements of the building under study as evidenced by its lowest NPC, COE, significant RE fraction of 82.6% and lowest CO_2 production, thereby reinforcing that which was found above.

Table 5. Hybrid System Optimization Results.

Parameter	Grid and 10 kW Wind Turbine	Grid only	PV and Grid	PV, (2) 10 kW wind turbines and Grid
NPC ($US)	12,596	16,704	16,744	30,022
COE ($US)	0.0443	0.0600	0.0601	0.0307
Operating Cost ($US /yr)	833.66	1,292	1,294	1,180
Initial Capital Cost ($US)	13,000	0	19.18	14,765
O&M ($US /yr)	693.74	1,292	1,293	801.97
Ren Frac (%)	82.6	0	0.0369	94.1
Electricity Produced (kWh/yr)	41,502	21,535	21,541	76,252
Excess Electricity (%)	0	0	0.0277	0.611
CO_2 (kg/yr)	4,569	13,610	13,605	2,842

Effect of Grid Prices on System Performance

Sensitivity analyses were performed on the various scenarios simulated previously by varying grid power prices from the subsidized rate (US$ 0.06/kWh) upwards to (US$ 0.40/kWh). Generally, increases in grid power price resulted in an increase in the renewable fraction and a consequential decrease in CO_2 emissions as one would expect. A detailed analysis from the application of the sensitivity analysis to the scenarios are presented.

Sensitivity Analysis of Renewable Energy Case 1- Grid with PV

Table 6. Grid Power Prices and corresponding system optimized by Homer Pro.

Grid power Prices (US$ /kWh)	0.06	0.12	0.20	0.30	0.40
Optimal System	Grid only	Grid only	Grid only	Grid only	Grid and PV

As shown in Table 6, application of increasing cost for grid power showed that the renewable system consisting of Grid and PV was favorable at the power price of US$ 0.40/kWh. Further details of the optimization results for this system at the power price of US$ 0.40/kWh are shown in Table 7. The data demonstrates that even though the Grid only scenario had the lower NPC, the Grid and PV system became more economical at this price with the system having a renewable fraction of 44.2%.

Table 7. Optimization Results for Grid and PV system chosen as most optimal.

Parameter	Grid and PV (7kW system with 5 kW converter)	Grid only
NPC ($US)	98,701	111,358
COE ($US)	0.339	0.400
Operating Cost ($US /yr)	6,290	8,614
Initial Capital Cost ($US)	17,389	0
O&M ($/yr)	6,168	8,614
Ren Frac (%)	44.2	0
Electricity Produced (kWh/yr)	23,538	21,535
Excess Electricity (%)	2.10	0
CO_2 (kg/yr)	7,945	13,610

Sensitivity Analysis of Renewable Energy Case 2- Grid with Wind Turbine.

Table 8. Grid Power Prices and corresponding system optimized by Homer Pro.

Grid power Prices (US$ /kWh)	0.06	0.12	0.20	0.30	0.40
Optimal System	Grid only	Grid and 1 wind turbine	Grid and 1 wind turbine	Grid and 1 wind turbine	Grid and 1 wind turbine

As shown in Table 8, application of increasing cost for grid power showed that the renewable system consisting of Grid with Wind Turbine was favorable at the power price of US$ 0.12/kWh and above. Further details of the optimization results for this system at the power price of US$ 0.12/kWh are shown in Table 9. The data clearly demonstrate that the Grid with Wind Turbine system was superior in all parameters when compared to the Grid only base scenario.

Table 9. Optimization results for Grid and Wind system chosen as most optimal.

Parameter	Grid and (1) 10kW Wind Turbine	Grid only
NPC ($)	29,384	33,407
COE ($)	0.0548	0.120
Operating Cost($/yrs.)	1,267	2, 584
Initial Capital Cost ($)	13,000	0
O&M ($/yr)	1,127	2,584
Ren Frac (%)	82.6	0
Electricity Produced (kWh/yr)	41,502	21,535
Excess Electricity (%)	0	0
CO_2 (kg/yr)	4,569	13,610

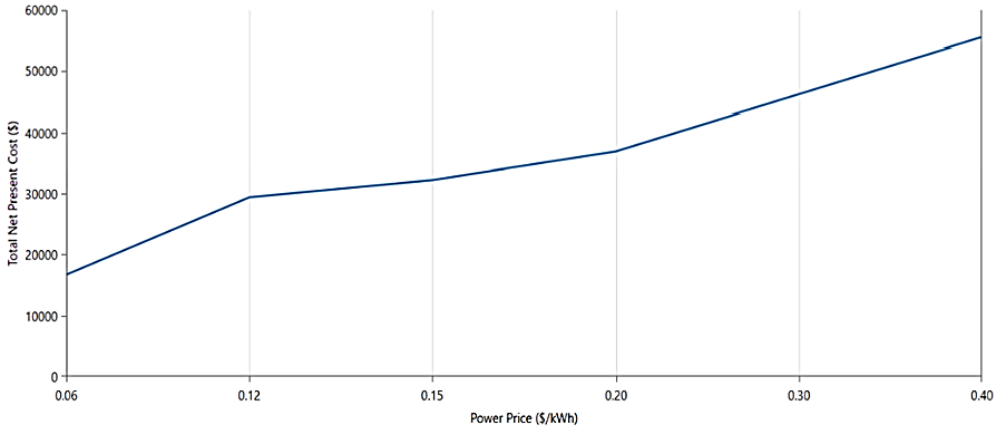

Figure 10. Total NPC vs. Power Price for the Grid and Wind Turbine System.

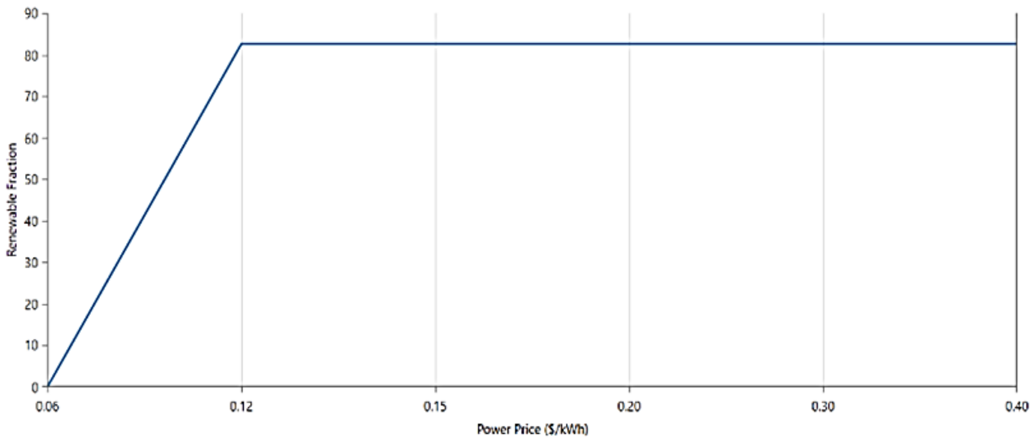

Figure 11. Renewable fraction vs. Power Price for the Grid and Wind Turbine System.

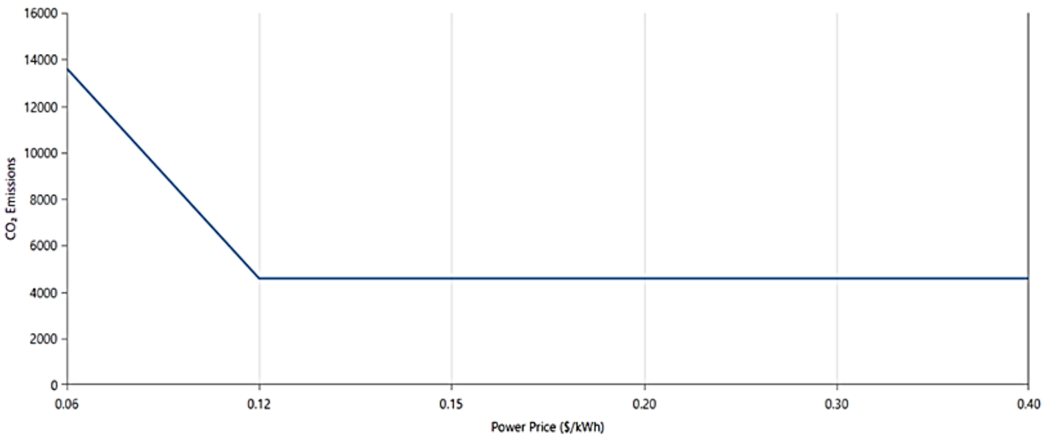

Figure 12. CO_2 Emissions vs Power Price for Grid and Wind Turbine System.

In terms of the NPC, Figure 10 demonstrates that the total NPC increases as the grid power price increases. At a grid power price of US$ 0.12, the Grid and Wind Turbine scenario is more favorable compared to the previously discussed Grid and PV system previously discussed due to its significantly lower NPC (US $98,701 for the Grid and PV vs $29,384 for Grid and Wind Turbine). The favorable changes with regards to higher renewable fraction (Figure 11) and decreases in CO_2 emissions (Figure 12) are demonstrated when the cost for grid power was increased from a price of US$ 0.12/kWh to US$ 0.40/kWh for the Grid and Wind Turbine scenario.

Sensitivity Analysis for Renewable Energy Case 3 - Grid with Wind and PV (Hybrid Model)

Table 10. Grid Power Prices and corresponding system optimized by Homer Pro.

Grid power Prices (US$ /kWh)	0.06	0.12	0.20	0.30	0.40
Optimal System	Grid only	Grid only	Grid and 1 wind turbine	Grid and 1 wind turbine	Grid and 1 wind turbine

As shown in Table 10, application of increasing cost for grid power showed that the renewable system consisting of Grid with Wind and PV (Hybrid Model) was favorable at the power price of US$ 0.20/kWh and above for the system configuration with Grid supply and wind only. Further details of the optimization results for this system at the power price of US$ 0.20/kWh are shown in Table 11.

Table 11. Optimization results for the system chosen as most optimal for the hybrid case.

Parameter	Grid and (1) 10kW Wind Turbine	Grid only	Grid and 0.0781 kW PV system	Grid and 2 kW PV System with (2) 10 kW Wind Turbines
NPC ($US)	53,140	55,679	55,888	93,081
COE ($US)	0.0990	0.200	0.201	0.0952
Operating Cost($US /yr)	3,105	4,307	4,311	4,820
Initial Capital Cost ($US)	13,000	0	153.44	30,765
O&M ($US /yr)	1,706	4,307	4,306	1,751
Ren Frac (%)	82.6	0	0.295	94.1
Electricity Produced (kWh/yr)	41,502	21,535	21,586	76,252
Excess Electricity (%)	0	0	0.221	0.611
CO_2 (kg/yr)	4,569	13,610	13,570	2,842

As shown in Table 11, at a grid power price of US$ 0.20, the wind turbine and grid option were economical at a renewable fraction of 82.6%. The results also indicated that an increase in the cost of energy caused the Grid only option to have a higher NPC and operations and maintenance cost this made the wind and grid system more economical. The hybrid system which was the grid, PV and wind turbine, was not economically feasible as the costs were very high. These types of systems will not be a viable option for the building under study.

Apart from the capital costs, due to the location of the building and its topography (located close to other buildings), the use of wind turbines will not be viable. For these reasons, the Renewable Energy Case 1- Grid with PV scenario was selected as the most appropriate strategy and this scenario will be the subject of further investigation.

The effect of subsidy levels on the performance of the Grid with PV system

The effect of subsidy levels on the performance of the Grid with PV system was studied by conducting sensitivity analyses on the modelled system using various grid power prices including a subsidized cost of US$ 0.06/kWh, the estimated unsubsidized cost of US$ 0.13/kWh, the average Caribbean rate of US$ 0.33/kWh, average rate in St. Lucia of US$ 0.38/kWh and a rate of US$ 0.43/kWh for Dominica. Table 12 shows the results of the sensitivity analyses.

Table 12. Sensitivity Results for unsubsidized costs for the Grid and PV system.

Parameter	Grid only	Grid only	Grid Only	7 kW PV, 4 kW converter and Grid	8 kW PV, 5 kW Converter and Grid
Power Price ($US /kWh)	0.06	0.13	0.33	0.38	0.43
NPC ($US)	16,704	36,191	91,870	95,402	103,486
COE ($US)	0.06	0.13	0.33	0.33	0.351
Operating Cost ($US /yr)	1,292	2,800	7,107	6,100	6,539
Initial Capital Cost ($US)	0	0	0	16,541	18,954
O&M ($US /yr)	1,292	2,800	7,107	5,984	6,410
Ren Frac (%)	0	0	0	42.3	47.4
Electricity Produced (kWh/yr)	21,535	21,535	21,535	23,329	24,063
Excess Electricity (%)	0	0	0	2.03	2.83
CO_2 (kg/yr)	13,610	13,610	13,610	8,150	7,578

The results show that as the cost of power increased from the current subsidized price of US$ 0.06/kWh which is currently applicable to the commercial business facility being studied in TT, operation and maintenance of the grid became progressively less favorable and at a cost of power of US$ 0.38/kWh, utilization of renewable energy began. At higher cost of power values, as the renewable fraction increased so was the corresponding amount of excess energy produced. The selected system was found to be the Grid coupled with the 7kW PV using a 4kW converter which reduced CO_2 emissions by 40% compared to the grid only case and had an associated renewable fraction of 42.3%.

The effect of the cost of the Grid with PV system on the on feasibility.

One of the drawbacks of the use of the Grid with PV system as shown in Table 12 is the high capital costs of the system due to the high customs fees and importation taxes associated with the importation of the equipment. A sensitivity was performed by reducing the PV cost from US$ 1,714 (the average cost for a 1kW PV system to a value of $US 1,200, incorporating a possible government subsidy of 30% [35]. The results of the sensitivity analyses are shown in Table 13.

The results clearly demonstrated that reducing the cost of the PV system had a significant positive impact on the economic feasibility (lower NPC) of the renewable energy systems as well as an improvement the associated values of renewable fractions. A favorable scenario was presented at a power cost of $US 0.33/kWh utilizing a 11.3kW PV, 5.63kW converter and Grid. This system, although having a higher cost of energy, produced more power with 7.14% excess electricity and reduced CO_2 emissions by 53% compared to the grid only case.

Table 13. Sensitivity Result for lower PV costs for the Grid and PV system.

Parameter	Grid only	Grid only	11.3 kW PV, 5.63 kW converter and Grid	12.9 kW PV, 6.17 kW converter and Grid	13.8 kW PV 6.38 kW converter an Grid
Power Price ($US /kWh)	0.06	0.13	0.33	0.38	0.43
NPC ($US)	16,704	36,191	71,956	78, 219	84,113
COE ($US)	0.06	0.13	0.232	0.243	0.257
Operating Cost ($US /yr)	1,292	2,800	4,087	4,378	4,731
Initial Capital Cost ($US)	0	0	19,125	21,625	22,947
O&M ($US /yr)	1,292	2,800	3,937	4,213	4,561
Ren Frac (%)	0	0	57.7	62.5	64.7
Electricity Produced (kWh/yr)	21,535	21,535	26,666	28,228	29,201
Excess Electricity (%)	0	0	7.14	8.86	10.2
CO_2 (kg/yr)	13,610	13,610	6,419	5,896	5,652

The effect of grid feedback (feed in tariffs) on the feasibility of the Grid and PV system

Different feed in tariff rates were incorporated into the analysis. These are shown in Table 14 and range from 18% of the grid purchase price to 66% of the grid purchase price. These were all analysed with gird prices exceeding US$ 0.33/kWh, as various permutations below that price were found to be uneconomical for an acceptable RE penetration.

The results show that at these costs of power, the feasibility improves as the sellback rate increases enabling more energy sold to be sold to the grid. The selected option is the 11.7kW PV with the 7.69kW converter and Grid at a grid power cost of US$ 0.33/kWh with a sellback rate of US$ 0.22/kWh. The renewable fraction of this is 62.2% and the excess electricity was 1.81%.

Table 14. Sellback price sensitivities at Power Prices of US$ 0.33/kWh, US$ 0.38/kWh and US$ 0.43/kWh.

Parameter	11.7 kW PV, 7.69 kW converter and Grid	7.95 kW PV, 4.88 kW converter and Grid	10.6 kW PV, 6.72 kW converter and Grid	14 kW PV, 9.04 kW converter and Grid	9.06 kW PV, 5.55 kW converter and Grid	12.1 kW PV, 7.54 kW converter and Grid	16.6 kW PV, 10.9 kW converter and Grid
Grid Power Price($US/kWh)	$US 0.33/kWh	$US 0.38/kWh			$US 0.43/kWh		
Sellback Rate ($US/kWh)	0.22	0.07	0.17	0.22	0.07	0.17	0.22
NPC ($US)	83,382	94,521	92,039	89,308	102,074	98,429	94,693
COE ($US)	0.252	0.321	0.290	0.250	0.338	0.297	0.240
Operating Cost(($US/yr)	4,297	5,880	5,191	4,349	6,265	5,431	4,271
Initial Capital Cost ($US)	27,828	18,501	24,930	33,090	21,080	28,217	39,474
O&M (($US)/yr)	4,092	5,750	5,012	4,108	6,117	5,230	3,980
Ren Frac (%)	62.2	46.5	58.2	68.5	51.6	62.9	74
Electricity Produced (kWh/yr)	26,903	23,829	25,860	29,310	24,612	27,221	32,370
Excess Electricity (%)	1.81	2.17	2.21	2.25	2.46	2.57	2.08
CO_2 (kg/yr)	6,108	7,691	6,490	5,510	7,150	6,017	5,017
Energy Purchased (kWh)	9,664	12,170	10,269	8,718	11,313	9,521	7,938
Energy Sold (kWh)	4,044	1,220	3,003	6,119	1,838	4,136	8,975

In summary, the simulation results for the grid connected cases showed the grid only option to be the best as a result of the current subsidized cost of energy in Trinidad and Tobago which was found to be US$ 0.06/kWh currently. This low grid power price made the renewable energy systems unattractive as they were uneconomical, in comparison to the grid only option. However, as the grid price was varied upwards the grid costs increased making the renewable systems more cost effective. In the case of the PV and Grid system, the PV started to be utilized at a power price of US$ 0.40/kWh. At this power price, the NPC was lower at US$ 98,701 compared to the Grid only option where the NPC was US$ 111,358. The renewable fraction was 44.2% with a reduction of CO_2 emissions of 42% compared to the grid only case. The Grid and wind turbine system started to be utilized at a power price of US$ 0.12/kWh. The renewable fraction was 82.6% at an NPC of US$ 20,384 CO_2 emissions were reduced by 66%. Compared to the grid only case, the hybrid case with the PV and converter, wind turbine and grid had a remarkably high net present cost and therefore these types of systems may not be practical to implement in the building of interest.

Although the best system based on the Homer Pro Simulation cases may have been the wind and grid option, the PV, with converter and grid was chosen as the best system to be used for the building under study, as the location was not ideal for a wind turbine system. Sensitivities with unsubsidized costs showed that for Trinidad and Tobago and the other Caribbean countries, we see that at higher power prices the renewable energy systems becomes more feasible and economic. For the Grid and PV with converter system, a 7kW PV, 4kW converter with the grid started to be utilized at a power price of US$ 0.38/kWh with a 42.3% renewable fraction, 2.03% excess energy and 40% reduction in CO_2 emissions. The load was varied at the different unsubsidized power costs, and this showed it was more economical to have the grid and PV system at the higher grid prices as the O&M would be less as well as the NPC. PV Initial cost was lowered to see the impact of this as well and it was seen that the PV system was utilized at a lower grid price as the PV cost decreased.

It was seen from the results that at the unsubsidized cost of electricity feed in tariffs would be beneficial and can be utilized to also increase the renewable fraction as private owners of RE systems can now feed energy to the grid for a reasonable price lower than the grid power price. It was seen that the Standalone PV system required batteries as well as a generator system in order to meet the load requirements of the building however the NPC and the O&M cost were extremely high. The 100% RE system had the highest NPC of US$ 243,961. At the current subsidized diesel price of US$ 0.50 per L the PV only system was not feasible but at the unsubsidized rate at diesel price in T&T of TT$ 0.78 per L the NPC was lower for when the PV system started to be used. This was for a renewable fraction of 46.3%. Based on the overall results for a renewable energy system to be utilized in any building in Trinidad and Tobago that the Grid power price needs to be higher and that will mean the gradual removal of current fuel subsidies as the transition is made to incorporate more renewable energy into the energy mix. Also, policies need to be put into place to make these systems more economically feasible by putting more incentives on them in terms of funding, tax debates, custom fees & charges for importation. Long term Trinidad and Tobago should look at feed in tariffs and net metering as well where customers can save on their electricity bills, however this will require special metering. The most feasible option for the building will be the PV and converter with the grid option.

4. Conclusion

At this present subsidized cost of electricity and without grid sellback, of all the RE systems analysed, only the wind system was economical, with a cost of energy (COE) of US$ 0.0443/kWh and RE penetration of 82.6%. However, the given site was not conducive to be fitted with a wind turbine due to space constraints. The solar PV system was economical at a much higher COE of US$ 0.339/kWh with a lower RE penetration of 44.2%, indicating no financial benefit to adopt a solar PV system at the site at both the subsidized rate and estimated unsubsidized rate of electricity ($US 0.12/kWh). When grid sell back is integrated, the PV system was economical at a much lower COE of US$ 0.252/kWh as opposed to without sellback (with a grid price of US$ 0.33/kWh at a sellback rate of US$ 0.22/kWh) with associated higher RE penetration of 62.2%. It can therefore be concluded that for a commercial site like this in Trinidad, the price of electricity from the grid would have to be over US$ 0.33/kWh or 5 times the present subsided cost to drive solar PV adoption from a purely economic viewpoint.

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