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Research Article

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Posted Date: June 12th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9998428/v1

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Additional Declarations: The authors declare no competing interests.

Optimising a Hybrid Renewable Energy System for a Telecommunication Site in Trinidad & Tobago: A Case Study

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Received: xx.xx.xxxx Accepted:xx.xx.xxxx

Abstract- There is a paradigm shift among global telecommunication operators to reduce their operational expenditure through more energy efficient practices while mitigating environmental degradation by reducing their carbon footprint. Related to this shift, this investigation looks at a techno-economic analysis for integrating a renewable energy system at a small satellite communication site in Trinidad and Tobago. This study aims to determine the most energy efficient hybrid design, to determine the feasibility of pricing various scenarios, and to quantify the CO_2 and renewable energy (RE) fraction for the various scenarios. To achieve this a synthetic energy load profile was developed using metered utility data and this was incorporated into the HOMER Pro software. Additionally, solar and wind resource statistics from NREL were accessed through HOMER and served as vital inputs for the modelling, simulation and optimisation of the proposed systems. At the present subsidised electricity rates for commercial customers of US0.061$/kWh, RE penetration was not found to be economical. Under this pricing

scenario, optimal electricity energy source was the grid, with the site using approximately 5260 kWh/year at an annual cost of US$320.84 and associated CO_2 emissions of 2945 kg. At an estimated unsubsidised price of US$0.19/kWh, while Solar PV was seen to be still uneconomical, RE from wind was shown to be feasible with a 51.7% RE fraction. Applicable to T&T, the optimally designed RE system at the site would still be uneconomical and the cost at which such a system starts to make economic sense was found to be US$0.15/kWh (with a 10% RE penetration). Using a regional average unsubsidised cost of US$0.22/kWh, the RE system makes became more economical, with a larger RE penetration of 36.2% and corresponding CO_2 savings of 222,328 kg/year. At sell back rates of 50% purchase rates, the lowest cost for economical RE penetration is lowered to US$0.14/kWh. These findings can help to guide future research in the field as well as responsible decision/ policy making in TT and the Caribbean region at large.

Keywords- Homer Pro, LCOE, IRR, NPC, Operating Cost, Payback, Emissions, PV Panel, Wind Turbine

1. Introduction

Global greenhouse gas (GHG) emissions have risen to unprecedent levels as a result of an increase in energy demand leading to population growth, industrialisation and pollution [1]. This has contributed significantly to the phenomena that is the enhanced greenhouse effect, leading to detrimental consequences on the environmental landscape as a result of the intensification of global temperatures and rising sea levels [2]. Although Small Island Developing States (SIDS) generate miniscule levels of greenhouse gases, Trinidad & Tobago (TT) is ranked 8th based on annual CO_2 emissions per capita [3].

Globally, the underlying cause of the aforementioned is directly linked to our dependency on fossil fuels. Particularly, energy derived fossil fuels as they account for 72% of GHG emissions which emanate from electricity and heat generation, transportation and manufacturing [4]. This dependency has also led to concerns about energy security as most countries lean heavily on imported oil and gas from relatively few exporting countries [5]. It should be noted that since Trinidad and Tobago is a tropical island state, most of its residential energy consumption is used for cooling [6].

Import dependency can result in supply disruptions, exposure to price volatility and variability which is further amplified by global & geopolitical uncertainties [7]. Such was the case in TT, spikes in energy prices from 2021 – 2022 resulted in an unprecedented 100% increase in the price of oil, frustrating policy makers as the fuel subsidy incurred a gapping financial deficit [8].

Internationally, there is a weighted emphasis on enhancing energy security and achieving net zero emissions, amplifying the imperative to swiftly transition to an efficient, sustainable-based energy system [9]. This system must be void of fossil fuel dependency such that consumers and the industry are not exposed to political pressures and price volatility while being compatible with ambitious climate goals [10].

In recognition of the harmful effects posed by global warming and climate change, the renewable energy agenda has gathered a surge of support from intergovernmental organisations worldwide [11]. Through economic stimulation and sustainability road maps, the IMF and the United Nations have aided in steering the pathway towards the rapid transition from fossil-fuels to renewable resources [12]. In keeping with the Paris Agreement, TT needs to investigate the potential use of other cleaner sources of energy consistent with strategic decisions and policies adopted by other countries around the

world. TT agreed to a reduction in GHG emissions by 15% across three main sectors, power generation, transportation and industry, by 2030 [13].

According to a study by Sakagami, Shimizu and Kitano electric vehicles are pivotal in the reduction of GHG emissions once the electricity generated by charging stations originate from RE [14]. The most attractive solution to efficiently use RE within the public transportation sector was identified as a solar powered EV charging station with exchangeable battery storage [15].

Alawad et. al. presented research highlighting the potential of RE to offset the power consumption of a desalination plant which is critical in averting water scarcity [16]. Research presented by Aros-Vera et. al. highlighted the significant role RE systems played during the landfall of Hurricane Maria on the island of Puerto Rico in 2017 [17]. Although the storm resulted in an extremely large outage of the main utility grid, RE systems were utilised in a distributed manner in order to mitigate the negative impact. Similarly in TT, the RE applications described in these case studies can be adopted to diversify the energy mix while reducing energy dependence from fossil fuel sources and by extension GHG emissions bring alignment with the goals outlined in the Paris Agreement [18].

Supporting the shift is a decline in technological cost as the price in terms of $/kWh has experienced consecutive year-on-year declines over the last decade for both photovoltaic (PV) and wind turbine (WT) systems [19]. Particularly vulnerable to the adverse effects of climate change are SIDS. The long-term risks associated with this event threatens to disrupt their energy security and destabilise their already vulnerable economies. While their contributions to climate change is insignificant, these countries must be proactive and take measures to mitigate its impacts, ensuring their survival and

prosperity [20]. On the contrary, SIDS such as TT are advantageously positioned to reap the benefits of renewable based technologies as they possess abundant sources of renewable energy [21].

There is a case for a pro renewable energy agenda within the telecommunication industry, particularly as it relates to radio frequency (RF) base stations. Driving this dialogue is the fact that radio base stations are the heaviest consumers of energy within the sector coupled with the growing demand for the utilisation of energy in an efficient, conservative and environmentally friendly manner [22]. This study presents the opportunity to explore the potential benefits of RE within the telecommunications sector of TT as there is a lack of research pertaining to its implementation.

There is a paradigm shift among global telecommunication operators to adopt more energy efficient practices aimed at reducing their operational expenditure through enhanced feasibility and reliability while mitigating environmental degradation by reducing their carbon footprint [23].

This research explores the potential for integrating a renewable energy power source at the San Pedro communications site located in TT. This case study involves the modelling, simulation, optimisation and economic analysis of varying system architectures for the designated site utilising the Homer Pro software suite. This will aide in determining the most energy efficient and economically viable configuration based on the examination of key metrics such as GHG emissions, cost parameters and performance metrics to meet the energy demands of the site. The utility of such a study can be underscored by the fact the telecommunication sites must be supplied with uninterrupted power supplies 24/7. Therefore, the impact of this study can guide future development of sustainable approaches to telecommunication deployment.

The key objectives of this study are:

1. Determine the most energy efficient hybrid design to supply the electricity needs of the site
2. To determine at what pricing scenario will make the adoption of a hybrid energy supply feasible.
3. To quantify the amount of CO_2 emissions that are made for each hybrid design.
4. To quantify the RE fraction that will be achieved for various hybrid scenarios.

2. Literature Review

The HOMER Pro software suite has been established as the global standard for the optimisation of energy generation systems. Additionally, numerous scholarly articles have documented its use case, specifically in the evaluation of grid-connected and stand-alone renewable energy systems used to power communication base stations in rural/remote regions throughout the world.

In a study conducted by Goel & Ali on the coastal state of Odisha, India, Homer Pro was utilised for the optimisation of hybrid renewable energy systems (HRES) based on a PV-Wind-Diesel design for three varying loads of 22kW, 55kW and 83 kW respectively [24]. The optimised system was compared against a diesel only generation system to determine the feasibility of the architecture through an economic analysis. The assessment parameters consisted of the net present cost (NPC), costs of energy (COE) and operating costs (OC) as well as the GHG emissions for each system was also analysed. In addition, the initial cost (IC) was also analysed. The results of this study concluded that a hybrid-based system resulted in a considerable economical advantage as it was able to achieved a lower NPC, COE, OC, excess electricity and lower GHG emissions when considering three different load sizes in comparison to the standalone

diesel system. Similarly, this strategy can be adopted to confidently select the most efficient RE systems for the communication site at San Pedro utilising Homer's ranked performance metrics.

Ennemiri et. al. performed an analogous study showcasing the prowess of the Homer Pro software suite for the optimisation of a PV/WT hybrid system [25]. The design was based on a standalone HRES for remote telecommunication stations in the country of Alegria. NPC, IC, OC and COE were the metrics considered in the economic analysis. Based on a net load of consumption of 4632 kWh/year, the simulation successfully models a HRES for each site capable of generating 9538, 8463 7903 and 8,843 kWh/year respectively. While the study demonstrates a positive outcome in modelling an RE system, there was no inclusion of a baseline system such as a diesel generator to provide a definitive comparison against. The research could have also brought coverage to the environmental impacts of transitioning to a RE power source by quantifying the current and mitigated GHG emissions.

The available literature highlights numerous applications of RE systems being adopted to power RF base stations in different regions globally, however there is a gap in the literature as it relates to the integration of such systems within the Caribbean and particularly in Trinidad and Tobago. The impact of discount and inflation rate on core economic parameters such as NPC and LCOE was under explored. This analysis can provide valuable insight into how RE investments can be navigated during inflationary and deflationary periods. The use of a generator schedule proved to be a significant factor in achieving a lower levelised cost of energy (LCOE), however it's use case was only identified in one study, presenting the opportunity to explore the possible advantage in this case study. Another noteworthy point is that the majority of research published

revolves around base stations for cellular network applications. The scope of this project relates to a communication site which provides Ultra High Frequency (UHF) point-to-point RF applications. Both communication applications are extremely similar in nature with respect to

- The radio frequency band being used to transfer information i.e., UHF band
- The information being transferred over RF i.e., Voice, Video, Data packets
- The base station system architecture, i.e., power supply, receiver, transmitter
- The site infrastructure, i.e., communication hut, tower, antenna

Hence, the optimisation methodology can be transposed with confidence for this specific case study.

From the literature, the utility of HOMER Pro to establish possible hybrid designs for various sites can be revealed. This exposes a gap in the literature in that no study was previously done to meet the needs of a telecommunication site using a hybrid energy approach in the country of TT. Therefore, for the first time, this research attempts to address this gap. In addition, this research can guide future development of sustainable telecommunication practices not only in TT but also for the rest of the Caribbean region.

3. Strategy and Development

The fundamental sequence of steps involved in the simulation of a communication site will be discussed employing a framework adopted in research presented by Boodlal et al. [26]

A. Simulation Strategy

1. Model existing system (Base Case)
2. Model ideal system
3. Comparative analysis of base case and ideal system

4. Outline recommendations for future work

B. Performance Metrics

1. Levelised Cost of Energy (LCOE)
2. Net Present Cost (NPC)
3. Payback
4. Operating Cost (OC)
5. Emissions

C. Key Input Variables

The simulation and optimisation of models proposed in this study will incorporate the following Homer Pro input parameters [26].

i) *Meteorological data* (solar, wind & temperature) obtained from NREL and NASA database specific to the location of the San Pedro site.

ii) *Component specifications*: equipment lifespan, PV panel, wind turbine, battery, inverter efficiency, capital cost, shipping cost, system operating and maintenance cost as tabulated in Table 1.

iii) *Fuel Cost*: Current subsidised diesel price at US$0.649/L in T&T and unsubsidised diesel price at US$1.140/L. World average diesel price at US$1.34/L [27].

iv) *Electricity Cost*: The rates tabulated in Table 2, were based on the average T&T subsidised rate, unsubsidised rate, average Caribbean rate, average world business rate and the rate of other named Caribbean islands [28]. As tabulated in Table 3, the proposed subsidised rates were derived from a median weighted average based on a study presented by Boodlal et al. [26].

The unsubsidised sellback rates, based on conservative values of ± 12.5% and ± 25% were logically derived from a study by [29] where 40%-50% of the base line scenario was considered.

Table 1. Component specification

Components	Characteristics						
	Technical Description	Capital Cost ($)	Capital Cost + CIF ($)	Cost($)/kW	Replace. Cost ($)/kW	O&M Cost ($)	Lifetime
Generator	90kW, 60Hz			267/kW	241/kW	0.05/year	15000 Hours
Battery	12V 200Ah	1069	-	1069	963	10	10 Years
PV Module	200W	249	446	2230/kW	0	30/kW/year	30 Years
Inverter	3kW, 24VDC - 120VAC	628	1057	353/kW	318/kW	0/kW/year	10 Years
Wind Turbine	1kW, 48VAC	1530				30/kW/year	20 Years
Controller	2kW, 48VAC - 120VAC	500				-	20 Years
Wind Turbine System		2030	3442	3442/kW	3098/kW	30/kW/year	20 Years

Table 2. Utility rates

Utility Variables	Utility Rate ($/kWh)
T&T Subsidized Rate	0.061
Global Average	0.135
Bermuda	0.237
Bahamas	0.253
Barbados	0.304
Jamaica	0.287
Cayman Islands	0.315
Median (Caribbean)	0.35

Table 3. Proposed subsidised and unsubsidised utility rates

Utility Variables	Utility Rate ($/kWh)
Subsidized Sellback	
Option 1	0.076
Option 2	0.113
Option 3	0.053
Option 4	0.046
Unsubsidized Sellback	
Option 1	0.214
Option 2	0.238
Option 3	0.166
Option 4	0.143

Economic Parameters:

Discount rate – 7.5% [30].

Rate of Inflation – 4.5% [31].

Rate deviation of ± 2% for discount and inflation rate is adopted from a study presented by Rao et. al. [30] and the carbon emission rate based on electricity generation in T&T from natural gas Seedath et. al. [32].

4. Methodology

1. Simulated Feasibility Study

This study consists of an energy load profile development and site assessment. The load profile for the San Pedro site was developed using utility bills spanning a minimum period of one year. Using metered data ensures a higher level of accuracy and prevents overestimation in relation to energy consumption. The site assessment evaluated the location for its renewable energy potential. Using HOMER Pro's statistical database, the average annual solar radiation, clearness index and wind speed were determined.

2. System Model Design

The existing system infrastructure will be modelled and simulated in Homer Pro, reflecting the developed load profile, the generator's rated capacity and the utility grid. Simulation outputs such as LCOE, CO_2 emissions, NPC, Capital Cost, OC and IRR will be reported on.

3. System Model Selection

Prospective models will be designed and simulated by modifying the base case through the integration of RE systems. Utility price sensitivities will be used to determine the lowest price the system will utilise RE. The following simulations will be considered however only one architecture would be chosen based on LCOE and NPC.

- Base case with PV and convertor

- Base case with wind
- Base case with PV, wind and convertor (hybrid).

4. Further Analysis

The winning RE system from step 3 will be used to further simulate scenarios for

i) Grid-feedback and appropriately justified grid sellback prices.

ii) Without Grid-feedback and varying unsubsidised prices.

iii) An equivalent standalone system

iv) Discount rate impact on LCOE and NPC

v) Inflation rate impact on LCOE and NPC

HOMER Pro's optimisation function will be used to guide the selection of the winning architecture from the pool of optimisation results based on varying performance metrics.

5. Sensitivity Analysis

Evaluate how different sensitivities such as utility, sellback, inflation and discount rates influence the performance of the system.

6. Economic and CO_2 feasibility analysis

An assessment of the proposed models and BAU model will be conducted to compare and contrast economic performance and CO_2 emissions

7. Selection of Winning Architecture

A comprehensive analysis of the prospective models will be conducted to determine the winning architecture for each scenario based on LCOE, IRR and NPC while giving consideration to the system's CO_2 emissions. However, the method of prioritising LCOE

as described in research presented by Boodlal et al. [32] for the selection of the winning architecture will be adopted.

5. Results

Feasibility Study - Simulated Energy Load Profile

The hourly energy requirements were generated via a synthetic load profile builder and injected into the HOMER Pro software. This data was simulated, accounting for natural variations by inputting appropriate day to day and time step random variabilities. The simulation results as illustrated in Figure 1 shows varying energy profile outputs based on daily, seasonal (monthly) and yearly time intervals. The daily profile indicates a rise in energy demand between 6AM-5PM which patterns a normal energy usage profile of the working class in Trinidad and Tobago. A consistent pattern was seen among the seasonal and yearly profile with Q4 being the most energy intensive period.

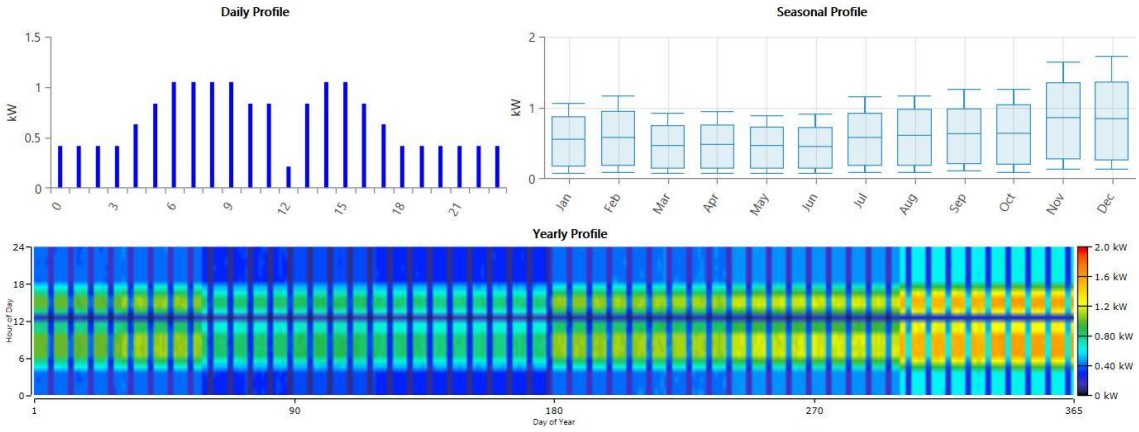


Figure 1. Simulated Load Profile

Feasibility Study – Simulated Site Assessment

Figure 2 illustrates the solar and wind resource availability at the site. The location experiences an average solar radiation of 4.96 kWh/m^2/day and an average clearness index value of 0.504. The maximum solar radiation is 5.58 kWh/m2/day which occurs in the month of April while the minimum level, 4.26 kWh/m2/day occurs in the month of November. The annual average wind speed is 7.13 m/s. The maximum wind speed recorded was 8.05 m/s which occurred in the month of February while a minimum wind speed of 5.85 m/s was registered in the month of September. The wind profile shows consistent speeds throughout the months of January – July, a noticeable decline is seen in the months of August – November, however the levels are sufficient enough for energy generation.

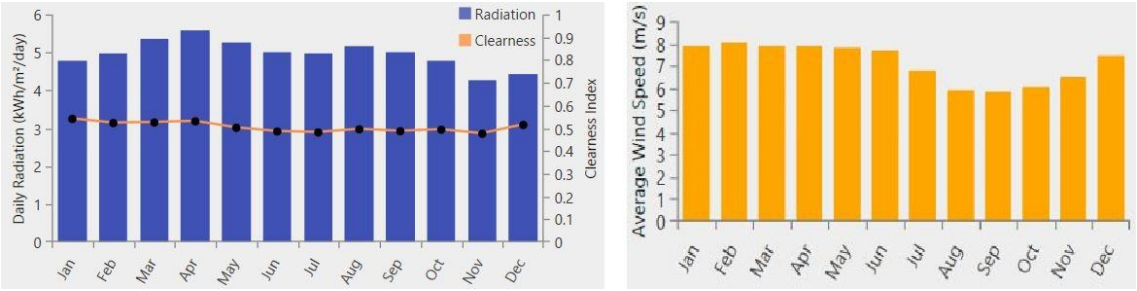


Figure 2. Solar and Wind resource data used.

Simulation Results

Base Case

The BAU model consists of an electric load which requires 14.41 kWh/d with a peak demand of 1.71 kW. The primary power source is provided by the electric grid at a cost of $0.061 USD per kWh. A 90-kW diesel generator is used as the secondary supply, operating at $0.651 USD per litre diesel. Although the system has a generator, it is

uneconomical to interchange power sources unless a grid outage occurs, hence, the actual base case is represented by the grid only model.

Investigation 1

This section builds upon the base case by introducing an individual PV, WT and Hybrid RE simulation scenario. These were accompanied by ascending grid price sensitivities to determine the minimal price at which RE was utilised. The corresponding price was then used to compare and contrast each model as seen in Table 4 and the most optimal system was selected. The hybrid case was modelled first to determine the minimal grid price the PV and WT would utilise together to accurately analyse these systems individually at the relative price sensitivity.

The hybrid simulation showed the most feasible scenario with a RF penetration (55.2%) occurred at a utility rate of $0.131 per kWh. This system was selected as the reference model for comparison between the individual PV and WT architecture.

The WT simulation when considering the reference model has NPC and COE stands at $17065 and $0.136/kWh respectively. The system has an IRR at 9.4% and simple payback time of 8.9 years at a renewable fraction rate of 51.7%. The model has an OC ($667), IC ($3442) and a CO_2 emission rate of 2082 kg/yr. The simulation illustrated that it was uneconomical for incorporating PV as this was only utilised at a much higher grid price of $0.19/kWh and even then at a lower 1% entry RE fraction.

Table 4. Comparative analysis of RE systems.

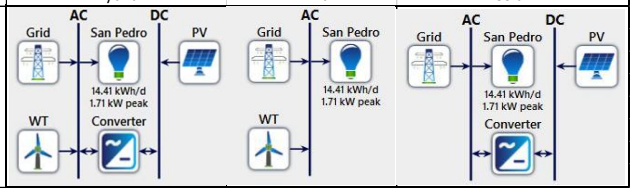
Metrics	Grid Price: $0.19		
	Hybrid	Wind	Solar
Simulated System Architecture			
Solar PV Capacity (kW)	0.193	-	0.0781
PV Mean Output (kW/d)	0.8	-	0.327
PV Prod. (kWh/yr)	295	-	119
Wind Turbine Capacity (kW)	1	1	-
Wind Turbine Production (kWh/yr)	3,181	3181	-
Electrical Consumption (EC) (kWh/yr)	6253	6155	5260
Excess Electricity (kWh/yr)	6.93	0	62
Renewable Fraction (%)	55.2	51.7	1
NPC (US$)	16705	17,605	20,459
LCOE (US$/kWh)	0.131	0.136	0.190
Operating Cost (US$/yr)	626	666	992
Initial Capital (US$)	3,917	3442	180
Internal Rate of Return (%)	9.2	9.4	-
Simple Payback (yr)	9.2	8.9	-
System Emissions (SE) (kgCO2/yr)	1959	2082	3643
Winning System Architecture	PV-WT-Grid	WT-Grid	Grid

Figure 3. Comparison of various scenarios simulated.

Optimal System Architecture

The hybrid configuration was determined to be the leading system based on the lowest associated NPC, LCOE and OC. Although the initial capital is 14% higher and the

simple payback period is roughly 3 months longer than that of the wind only system, the savings incurred through lowered cost parameters compensate for this. The system has a marginally higher RE value resulting in 6% less CO_2 emissions. The cumulative cash flow trend as seen in Figure 4 shows how the hybrid system conserves capital over the project's lifetime in comparison to the BAU scenario at the relative price and reflects graphically, the simple payback period of (9.2 yr.) which is denoted by the intersection of the two lines.

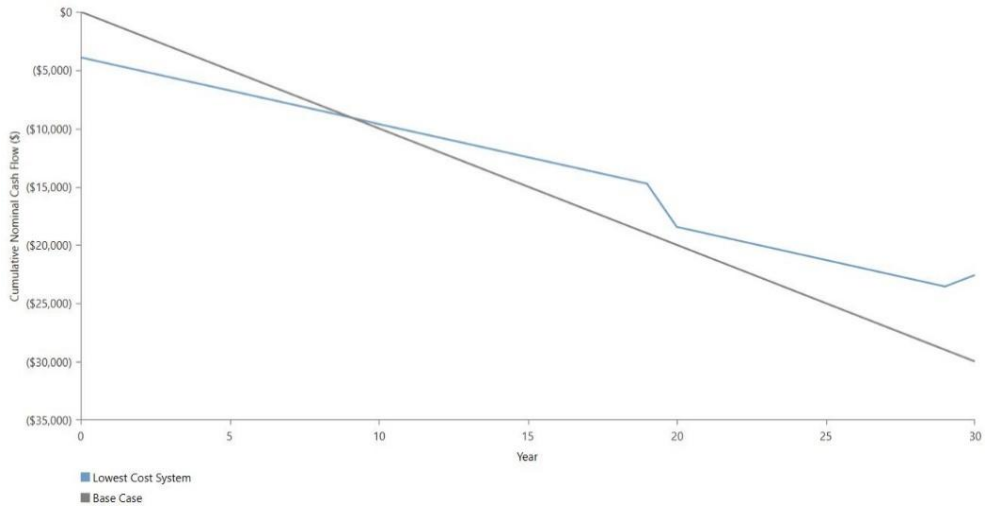


Figure 4. Cumulative cash flow trend

Investigation 2

This section builds on the winning hybrid architecture and its associated grid price by performing further economic analysis for

(i) Unsubsidised grid sensitivities (Without Grid Feedback)

(ii) Unsubsidised grid sensitivities (With Grid Feedback)

Scenario 1 - Unsubsidised grid sensitivities (Without Grid Feedback)

This investigation explores how the Base RE system and its associated estimated unsubsidised grid price of $0.19/kWh performs when higher utility rate sensitivities are introduced commensurate with different utility rates throughout the Caribbean. The results are seen in Figure 5.

Power Price ($/kWh)	System	PV (kW)	WT	Grid (kW)	Converter (kW)	NPC ($)	COE ($)	OC ($/yr)	IC ($)	Ren Frac (%)	CO2 (kg/yr)	IRR (%)	Simple Payback (yr)
0.19		0.19	1		0.129	16,705	0.131	625	3917	55.2	1959	9.2	9.1
0.237		0.56	1		0.356	19,238	0.145	705	4813	61.2	1760	11.2	8.0
0.253		0.65	1		0.423	20,049	0.150	734	5040	62.6	1717	11.9	7.6
0.287	PV-WT-G	0.85	1	999999	0.534	21,710	0.158	792	5521	65.2	1634	13.2	7.0
0.304		0.96	1		0.594	22,510	0.162	818	5783	66.5	1592	13.7	6.8
0.315		1.02	1		0.638	23,015	0.164	835	5945	67.3	1568	14.1	6.7
0.35		1.23	1		0.738	24,579	0.171	887	6442	69.5	1499	15.1	6.3

Figure 5 Grid sensitivity simulation results.

The simulation results show how an upward trend in utility prices influence the performance parameters of a system. Rising prices correlate to an uptrend in cost parameters such as NPC, COE, OC and IC. However, observations indicate that at higher utility rates, renewables become more affordable as the associated costs experience a slower rate of change causing a plateauing effect. The system is less reliant on the grid which drives the Renewable Fraction (RF) higher. In this scenario the IRR experiences steady growth, this provides a positive impact as the payback time falls.

Scenario 2 - Unsubsidised grid sensitivities (With Grid Feedback)

This section simulates a Feed in Tariff scenario by implementing sellback price sensitivities. Changes linked to the project's economic viability are explored for both subsidised and unsubsidised utility rates, leading to the selection of a winning architecture for each scenario.

Sell Back Prices (Unsubsidised Scenario)

The proposed sell back prices highlighted in Table 5 are associated with the unsubsidised RE base utility rate of $0.19

Table 5. Proposed sellback prices for the unsubsidised scenario.

	Cost ($)	Note
Option 1	0.03	Based on a 50% discount of present grid price.
Option 2	0.092	Based on a 50% premium of present grid price.
Option 3	0.166	Based on a 12.5% discounted price of T&T unsubsidised RE base utility rate.
Option 4	0.143	Based on a 25% discounted price of T&T unsubsidised RE base utility rate.

Table 6. Comparative analysis for unsubsidised sellback sensitivities.

Metrics		Unsubsidised Scenario					
	Grid Price	$0.19					
	Sellback Price	$0.030	$0.092	$0.166	$0.143	0.115	0.08
System Architecture		PV-WT-G	WT-G	PV-WT-G			WT-G
Solar PV Capacity (kW)		0.4	-	15	14.5	4.09	-
PV Mean Output (kW/d)		1.72	-	62.8	60.6	17.1	-

PV Prod. (kWh/yr)		628	-	22,933	22,112	6250	-
Wind Turbine Capacity (kW)		1	90				
Wind Turbine Production (kWh/yr)		3,181	286,300				
Electrical Consumption (EC) (kWh/yr)		6,385	286,888	307,289	306,778	292,950	288,866
Excess Electricity (kWh/yr)		13	0	1192	910	93	0
Renewable Fraction (%)		59	99.8	99.9			99.8
NPC (US$)		16,056	-61,312	-508,072	-366,025	193,967	7806
LCOE (US$/kWh)		0.123	-0.011	-0.081	-0.058	-0.032	0.001
Operating Cost (US$/yr)		568	-18,145	-41,780	-34,776	-25,126	14,765
Initial Capital (US$)		4,457	309,780	346,407	345,209	319,904	309,780

Internal Rate of Return (%)		9.3	4.6	13.0	10.0	7.4	3.0
Simple Payback (yr)		9.0	13.0	7.2	8.4	10	15
System Emissions (SE) ($kgCO_2/yr$)		1833	411	234	235	280	411

An analysis of the unsubsidised sellback scenario as highlighted in Table 6 above showed that the optimal system for the given sensitivities were profitable above and below $0.19 base utility rate. This indicates that policy holders can easily incentivised the adoption of RE while requiring minimal government funding. The data points from the current analysis were refined and it was determined that the lowest offer by policy makers to attain 100% RF occurred when the LCOE was $0.115 or -40% below the base utility rate when prioritising a PV-WT-G architecture. Above this price results in unnecessary compensation for the same RF unless the goal is to onboard RE suppliers through lucrative incentivisation rates. Below this price results in less profit for RE suppliers and greater savings for policy makers. However, this can result in slowed growth when it comes to the RE transition. The break-even scenario for both parties where LCOE is practically $0 was determined to be at a sellback rate of $0.08. Here, no monetary incentives are required by policy makers and RE suppliers don't profit from selling back to the grid. However, 100% RF is still possible if a WT-G architecture is considered.

Sell Back Prices (Subsidised Scenario)

The proposed sell back prices tabulated in Table 7 are associated with the subsidised BAU utility rate of $0.0610c.

Table 7. Proposed sellback prices for the subsidised scenario

	Cost ($)	Note
Option 1	0.076	Median value between the subsidized present and proposed T&T utility rate
Option 2	0.113	Median value between proposed subsidised T&T and global average utility rate
Option 3	0.053	Based on a 12.5% discount of T&T subsidized utility rate
Option 4	0.046	Based on a 25% discount of T&T subsidized utility rate

Winning Architecture (Subsidised Scenario)

Table 8. Comparative analysis for subsidised sellback sensitivities

Metrics		Subsidized Scenario					
	Grid Price	$0.06					
	Sellback Price	$0.076	$0.113	$0.053	$0.046	0.118	0.081
System Architecture		G	WT-G	G	G	PV-WT-G	WT-G
Solar PV Capacity (kW)		-	-	-	-	4.33	-
PV Mean Output (kW/d)		-	-	-	-	18,2	-
PV Prod. (kWh/yr)		-	-	-	-	6626	-
Wind Turbine Capacity (kW)		-	90	-	-	90	90
Wind Turbine Production (kWh/yr)		-	286,300	-	-	286,300	286,300
Electrical Consumption (EC) (kWh/yr)		-	286,888	-	-	292,879	288,866
Excess Electricity (kWh/yr)		-	0	-	-	118	0
Renewable Fraction (%)		-	99.8	-	-	99.9	99.8
NPC (US$)		-	-183,820	-	-	-212,655	496
LCOE (US$/kWh)		-	-0.031	-	-	-0.036	0.000
Operating Cost (US$/yr)		-	-24,135	-	-	-26,068	-15,122
Initial Capital (US$)		-	309,780	-	-	320,497	309,780
Internal Rate of Return (%)		-	7.1	-	-	7.5	2.8
Simple Payback (yr)		-	11.0	-	-	10	15
System Emissions (SE) (kgCO2/yr)		-	411	-	-	277	411

Table 8 above provides a comparative analysis for the subsidised sellback scenario. Analysing the subsidised sellback scenario for the BAU utility rate of $0.061

highlights that for sellback rates of $0.046, $0.0530 and 0.076 the grid only was determined to be the optimal system. The benefit of a lower LCOE was outweighed by the NPC, high capital costs, component replacement costs and long payback periods deeming it unfeasible to deploy an RE system for each scenario. The only sellback rate above the grid price which stimulates RE adoption was of $0.113. At this price, RE sellers experience monetary savings as well as a financial incentive but this is isolated to a WT-G configuration. Further analysis was performed to determine the sellback price where a PV-WT-G architecture would be feasible and this was determined to be $0.118 or 93% above the BAU price. This is also the lowest offer policy makers can pitch to attain a hybrid system offering 100% RF. Also, a sellback rate of $0.081 or 33% above the BAU price results in a near 0 LCOE rate, this does not incentivise RE through profit but creates an environment where RE sellers benefit through extremely low costs of energy while policy makers still benefit from 100% RF at minimal cost.

Investigation 3 - Impact of Discount and Inflation Rate

This investigation explores how the performance of the hybrid system from investigation 2 is affected by varying the rate of inflation and the discount rate while maintaining the corresponding utility price.

Impact of Discount Rate

The discount rate is the interest rate outlined by a commercial bank on capital an individual borrows. The discount rate was varied by +2% and -2% for the respective high and low discount scenarios as depicted in Figure 6 below.

Sensitivity	Architecture								Cost				System		Compare Economics	
NominalDiscountRate (%)					PV (kW)	WT	Grid (kW)	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	CO_2 (kg/yr)	IRR (%)	Simple Payback (yr)
5.50					0.515	1	999,999	0.329	CC	$20,457	$0.119	$589.46	$4,707	60.5	1,782	8.0	10
7.50					0.193	1	999,999	0.129	CC	$16,705	$0.131	$625.24	$3,917	55.2	1,959	9.2	9.1
9.50						1	999,999		CC	$13,899	$0.140	$648.38	$3,442	51.7	2,082	10	8.5

Figure 6. HOMER Pro Simulation results for discount rate impact

Given a constant utility and inflation rate, as the discount rate trends from low – high, NPC trends lower while LCOE trends higher and vice-versa as shown in Figure 7.

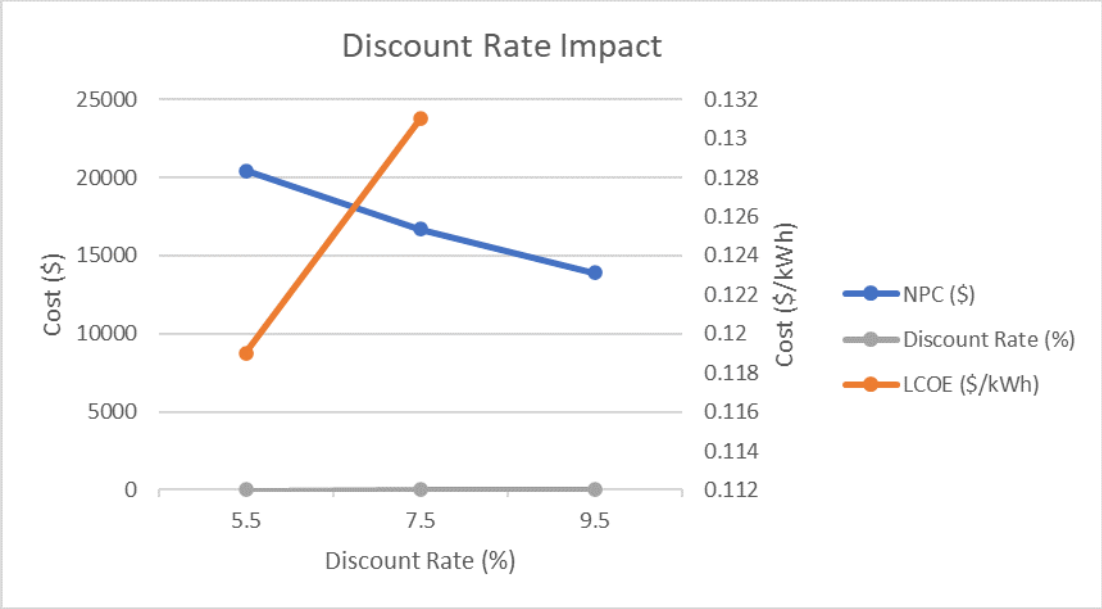


Figure 7. Impact of discount rate on NPC and LCOE

Impact of Inflation

Inflation is the surge in prices of goods and services in a country. It is also attributed to the decline of purchasing power of a currency for a country. The rate of inflation was varied by +2% and -2% for the respective high and low inflation scenarios as seen in Figure 8.

Sensitivity	Architecture								Cost				System		Compare Economics	
ExpectedInflationRate (%)				PV (kW)	WT	Grid (kW)	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	CO_2 (kg/yr)	IRR (%)	Simple Payback (yr)
2.70					1	999,999		CC	$13,788	$0.140	$648.24	$3,442	51.7	2,082	10	8.5
4.70				0.193	1	999,999	0.129	CC	$16,705	$0.131	$625.24	$3,917	55.2	1,959	9.2	9.1
6.70				0.514	1	999,999	0.333	CC	$20,489	$0.119	$589.47	$4,706	60.5	1,782	8.0	10

Figure 8. HOMER Pro Simulation results for impact of inflation rate

Given constant utility and discount rate, as the rate of inflation trends from low – high, NPC trends higher while LCOE trends lower and vice-versa as depicted in Figure 9.

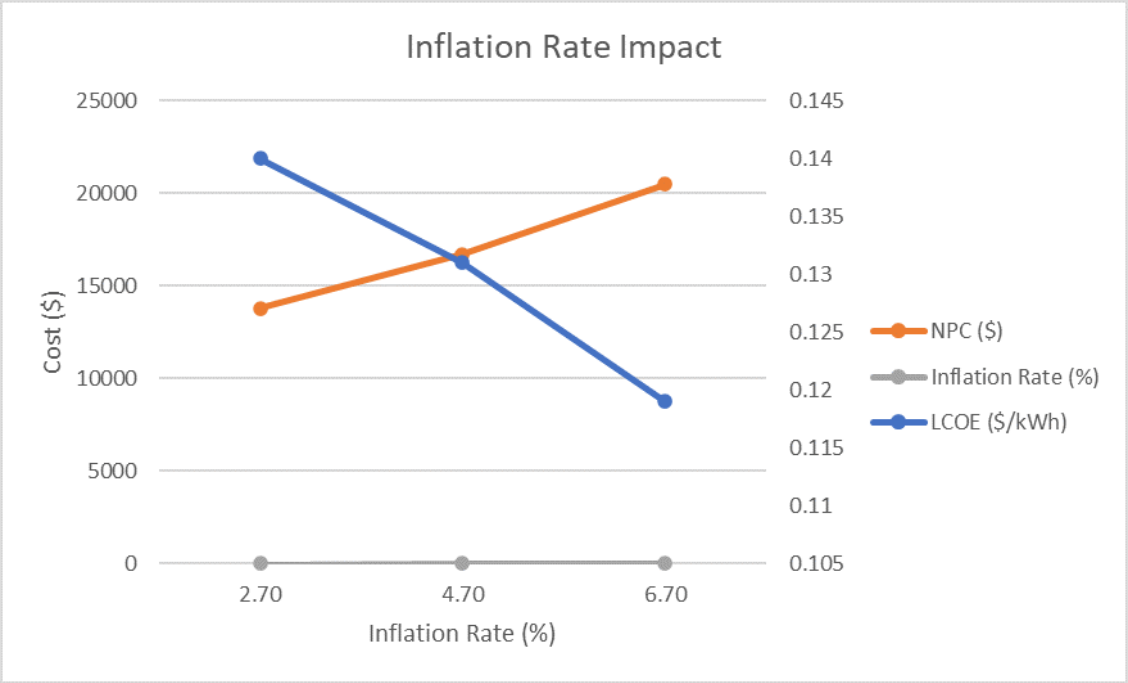


Figure 9. Impact of inflation rate on NPC and LCOE

Investigation 4 - Stand Alone System Analysis

This section investigates how the stand-alone variant as illustrated in Figure 10 performed in comparison to its grid connected counterpart for subsidised and unsubsidised utility rates yielding 100% RF when considering grid feedback.

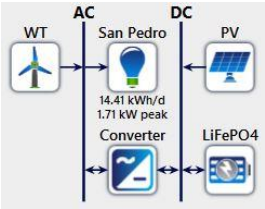


Figure 10. Standalone hybrid model

The most optimal standalone system was determined to be a PV/WT/BAT. The chosen architecture has a NPC $75,433, OC $1438 and an IC $46,014. Most importantly, the LCOE for 100% RE in this case was identified as $0.702. The cash flow graph as seen in Figure 24 illustrates the outflow of capital over the project's lifetime by components. Aside from the initial capital required during inception, the major outflows occur as a result of the wind turbine and battery replacement costs during the 10- and 20-year mark respectively. The only inflow is as a result of salvage capital at the end of the project's lifetime.

6. Discussion

Data obtained from the load analysis and feasibility study remained constant throughout the simulations while the technical and economic parameters were altered using various sensitivities to achieve the desired results for each simulation scenario. Table 9 highlights a comparative analysis of the standalone system when compared against its grid-tied counterpart for instances where 100% RE was achieved at the present subsidised ($0.061) and unsubsidised ($0.19) utility rates and their associated sellback prices. Additionally, the BAU model and the base RE price without a sellback variable

was considered to examine how these configurations compared against their sellback equivalent models and the standalone system.

Table 9. Comparative analysis for grid-tied, standalone and BAU models

			Subsidized Scenario		Unsubsidized Scenario			Off-Grid
	Grid Price	Present Subsidized Rate			Base Hybrid Rate			
Metrics	Sellback Price	0	0.081	0.118	0	0.08	0.115	
System Architecture		G	WT-G	Hybrid-G	Hybrid-G	WT-G	Hyrbid-G	H-BAT
Solar PV Capacity (kW)			N/A	4.33	0.193	N/A	4.09	7.83
PV Mean Output (kW/d)			N/A	18.2	0.8	N/A	17.1	32.8
PV Prod. (kWh/yr)			N/A	6626	295	N/A	6250	11,973
Wind Turbine Capacity (kW)			90	90	1	90	90	5
Wind Turbine Production (kWh/yr)			286,300	286,888	3181	286,888	286,300	15906
Electrical Consumption (EC) (kWh/yr)		5260	286,300	292879	6253	286,888	292,549	5257
Excess Electricity (kWh/yr)			0	118	6.93	0	93	22432
Renewable Fraction (%)			99.8	99.9	55.2	99.8	99.9	100
Battery Quantity			N/A	N/A	N/A	N/A	N/A	10
Autonomy (Hrs)			N/A	N/A	N/A	N/A	N/A	32
NPC (US$)		6562	496	-212654	16705	7806	-193966	75433
LCOE (US$/kWh)		0.061	0.000	-0.036	0.131	0.000	-0.032	0.700
Operating Cost (US$/yr)		321	-15122	-26068	626	-14765	-25126	1438
Initial Capital (US$)		$0	$309,780	$320,497	3917	$309,780	$319,904	$46,014
System Emissions (SE) (kgCO2/yr)		3682	411	277	1959	411	280	0

The comparison between the standalone system and WT-G configuration which represents the sellback price of $0.081 immediately shows the latter to be the more economical solution as this scenario is modelled off a low-cost energy environment. Although the IC is 573% more than that of the standalone system, a minimal NPC and

near $0 LCOE compensates for the high upfront cost. The project benefits from heavy operational cost savings and minimal CO_2 emissions annually. In comparing the Hybrid-G model and its associated sellback price of $0.118 the economic edge is even more apparent when examining LCOE, NPC and OC. The benefits experienced through monetary savings and incentivisation are astronomical and are only blemished by an exceedingly high IC requirement.

The BAU model is unmatched when comparing core economic parameters such as NPC and LCOE which are magnitudes less than the standalone system at 1050% and 1051% respectively. The utility rate is simply too cheap to consider the aforementioned system where grid power is readily available. However, the BAU model is outperformed when paired against each sellback scenario within the same category. The only immediate disadvantage stems from the high IC requirement, though, this cash outflow is offset for the $0.118 scenario due to revenue exceeding cost across core economic parameters. The $0.081 scenario does not offset the IC outflow but is practically at the point of break-even as the NPC is extremely low. The CO_2 emissions as expected are considerably less as both cases are based on at or near 100% RF.

Observations made from comparing the $0.08 sellback rate and its associated WT-Grid configuration and the standalone system highlighted metrics similar to the equivalent subsidised low-cost of energy scenario. The NPC in this instance saw a noticeable increase when cross compared but remains significantly lower (866%) than that of the standalone system. relatively equal when cross comparing the subsidised case. Operational cost remained relatively equal when cross compared to the subsidised case, the model continued to benefit from monetary savings as a result of annualised revenue exceeding cost. Analysing the Hybrid-Grid architecture in relation to its $0.115 sellback

price shows similar parameters when compared to the standalone and cross compared with the equivalent subsidised model. Attractive monetary savings throughout the project's lifetime from OC and NPC are experienced. Grid sales continued to be profitable based on a LCOE rate of -$0.032 as the annualised cost of producing electricity does not result in cash outflow while IC, similar to the subsidised case is substantially higher than what is required for the standalone system.

For extensive purposes, although RF stood at 55%, a comparative assessment of the Hybrid-Grid architecture without a sellback price was completed. The examination revealed a smaller system in terms of capacity as well as greater CO_2 emissions which is to be expected. The design doesn't benefit from financial savings or incentives when examining NPC, OC and IC which indicates the overall cost exceeds revenue. The system realises a significantly cheaper LCOE in contrast to the standalone variant at $0.131 or 81% less. When compared against the simulation results of the present BAU grid model, without a sellback price the system's only competitive edge is 74% less emissions. The core parameters are 115%,155% and 95% higher for LCOE, NPC, OC respectively when paired against the present grid configuration.

The simulated energy load profile derived from metered utility data was able to accurately capture the energy consumption of the load. Historical solar and wind resource trends via HOMER Pro's internal database proved the location is suitable for harnessing RE. Scholarly articles offered insights into the architecture of RES and steered the simulation and modelling techniques while highlighting successful case studies where HOMER Pro was the preferred software in the build of such designs. This knowledge was then applied to model, simulate and optimise ideal system configurations to power the existing load. The results allowed a comparative analysis of the proposed systems and

the BAU model where the outcome of the research definitively shows the hybrid model is the most ideal configuration when considering a grid-tied system across all scenarios and sensitivities presented. The hybrid model is superior to the standalone model based on economic performance. The LCOE associated with the standalone model is 101% higher than the average Caribbean utility rate and 1051% higher than the present BAU utility rate. The BAU model is outperformed against all scenarios where a sellback price is present. A low-cost of energy environment where LCOE is near $0 while maintaining 100% RE is attainable and represents a breakeven scenario for RE suppliers & policy makers. The impact of inflation and discount rates are crucial metrics to consider when evaluating RES.

The implications of this study dictate that BAU grid rate of US$ 0.0610 stagnates the growth of RE as the COE is simply too cheap. RES are only economically viable when the COE is greater than or equal to the unsubsidised price US$ 0.12 without grid feedback. REFIT will hasten the adoption of RE within the country, presenting policy makers with flexible options especially when considering the impact of inflation and discount rates on NPC and LCOE. The limitations of this study include unknown land space requirements for accommodating the configurations presented in this study due to physical site access restrictions. This limitation is present once more with respect to whether the communication tower has sufficient space to facilitate the installation of additional equipment e.g., solar panels.

7. Conclusion

Global telecom companies are adopting a new paradigm that aims to mitigate environmental deterioration by lowering their carbon footprint and lowering operating costs through more energy-efficient practices. This study examines a techno-economic

analysis for installing a renewable energy system at a small satellite communication facility in Trinidad and Tobago in relation to this change. Using metered utility data, a synthetic energy load profile was created and added to the HOMER Pro program. Furthermore, HOMER provided access to NREL's solar and wind resource information, which were essential for the modelling, simulation, and optimisation of the suggested systems. It was determined that the adoption of renewable energy (RE) was not cost-effective at the current subsidised electricity rates for commercial consumers of US0.061$/kWh. According to this price scenario, the grid was the best source of electricity for the site, which used about 5260 kWh annually at a cost of US$320.84 and produced 2945 kg of CO_2 emissions. While solar PV was still considered unfeasible at an estimated unsubsidised price of US$0.19/kWh, wind-powered RE was demonstrated to be viable with a 51.7% RE share. According to T&T, the best-designed RE system at the location would still be unprofitable, and it was determined that, at a 10% RE penetration, the cost at which such a system begins to make sense is US $0.15/kWh. With a higher RE penetration of 36.2% and associated CO2 savings of 222,328 kg/year, the RE system becomes more cost-effective when using a regional average unsubsidised cost of US$0.22/kWh. The lowest cost for cost-effective RE penetration is reduced to US$0.14/kWh at 50% buyback rates. Based on the specific objectives of the study, namely, to determine the most energy efficient hybrid design, to determine the feasibility of pricing various scenarios, and to quantify the CO_2 and RE fraction for the various scenarios, it can be seen that the results obtained relevant and useful in the global shift toward sustainable energy practices. Therefore, such findings help to guide future research in the field as well as responsible decision/ policy making in TT and the Caribbean region at large.

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