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Evaluation of a Renewable Energy System for Residential Purposes in Rural Trinidad and Tobago, West Indies

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ABSTRACT

As Trinidad and Tobago (TT) navigates the complexities of transitioning its energy mix, the interplay between global climate commitments outlined in the Paris Agreement, combined with efforts to achieve its Nationally Determined Contributions (NDCs) and reduce Greenhouse Gas (GHG) emissions associated with the electricity sector has become increasingly crucial. This case study evaluates the role of Renewable Energy (RE) resources in reducing GHGs in the residential electricity sector of TT. Energy data was utilised to create a simulated load profile of a base model using Hybrid Optimisation Model for Multiple Energy Resources (HOMER) Pro. The base model conducted comparative load analyses simulating various grid-tied and stand-alone RE systems and examined economic and environmental impacts via sensitivity analyses. The simulated 94.9% RE hybrid grid-tied system with a 3 kW wind turbine, 0.96 kW photovoltaics (PV) and 0.69 kW converter performed the best, with the potential to reduce GHGs by 50% (670.535 kg CO_2 per year). Simulations incorporating grid sellback and unsubsidised grid purchase prices required larger PV capacity (12 kW) and reduced wind capacity (3 kW), resulting in net CO_2 emissions of 682.536 kg CO_2 per year). Simulated stand-alone systems require significantly higher RE capacities coupled with energy storage and thus are not financially viable for TT. Lastly, the Levelised Cost of Electricity (LCOE) analysis showed that wind turbines have the greatest impact on GHG savings. These findings are crucial and highlight the potential of RE to reduce GHGs, achieve TT's NDCs and enhance energy independence, and play a vital role in informing policy.

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1 INTRODUCTION

The steadily increasing global population, coupled with continuous economic growth, has resulted in increasing demand and consumption of energy[1]. An estimated 80% of this energy is generated via the combustion of fossil fuels[2] which results in significant Greenhouse Gas (GHG) emissions that negatively impact the environment through global warming[1,3,4] and climate change. Consequently, several global initiatives have been launched to reduce GHG emissions, such as the Paris Agreement. Most countries that have ratified the Paris Agreement are required to submit a climate action plan or Nationally Determined Contribution (NDC) that outlines the actions the country will undertake to meet the goals of the treaty and build resilience to the impacts of increasing global temperatures[5]. As a fossil fuel-based economy, Trinidad and Tobago (TT) is heavily reliant on fossil fuels for power generation and export commitments. However, the country is faced with declining oil and natural gas reserves, which pose a significant challenge in balancing the domestic energy needs and export commitments, the latter of which is vital to the nation's revenue generation. The incorporation of renewable energy technologies (RETs) into the national energy mix would, therefore, aid in reducing the fossil fuels required for power generation while simultaneously increasing the available resources for export. Moreover, as a result of its thriving industry, TT has been ranked seventh in the world (on a CO_2 per capita basis) and produces an estimated 40 million tonnes of CO_2 annually[6]. In an effort to facilitate a more sustainable socio-economic future, TT, as a signatory to the Paris Agreement, was one of the first few countries to develop a NDC implementation plan. The National Development Strategy, finalized in 2014, commonly known as VISION 2030[7], was established by the Government of the Republic of Trinidad and Tobago (GoRTT), of which two of the short, medium, and long-term goals outlined, are a reduction in the national carbon footprint and an increase in the country's resilience to climate change[7]. Studies have identified the power generation, transportation, and industry sectors as the major contributors to GHG emissions in TT[7]. Thus, TT's intended NDC is based on the Carbon Reduction Strategies for these sectors, as well as implementing provisions outlined in the National Climate Change Policy. The aim is to reduce emissions from all three sectors by 15% from Business As Usual (BAU) operations by the year 2030[5].

Power consumption in the residential sector in TT accounts for approximately 29% of total electricity consumed, with an average household consumption of 16.6 kWh per day[8]. Of the estimated 400,000 households, 43% consume more than 1,000 kWh of electricity bi-monthly. This accounts for 70% of residential power consumption in TT, which is comparable to the electricity consumption of an average North American home[9]. This is quite high when compared with Caribbean standards and may be attributed to the current low cost of electricity due to existing subsidies, which contribute to the cheap rate of $0.052 per kWh available to the local population[10], coupled with the lack of public knowledge regarding energy efficiency and the need for energy conservation. Electricity prices in TT are currently subject to cross-sector subsidization, which results in a significant distortion between electricity consumption and the grid purchase price across sectors, whereby industry usage contributes to the subsidy applied to residential and commercial consumers, and vice versa. Consequently, this sub-sector is a notable contributor to the country's carbon footprint, thus a prime target for mitigation measures such as transitions to cleaner, RE alternatives[11]. High energy consumption, coupled with declining hydrocarbon resources[12], has resulted in increased costs of electricity production and thus, an increased financial burden to maintain the low cost of electricity in TT. As such, this has led to a planned removal of existing subsidies[13]. These contributing factors have resulted in increased interest in RE systems, and several Caribbean countries have incorporated RETs into their energy mix, with some large-scale projects that focus on single technology systems[14]. Similarly, in TT, single technology systems, such as solar and wind, have been the cornerstone of most RE efforts[15,16]. However, it is important to note that current legislation in TT does not permit grid-tied RE systems, nor are there provisions for sellback of excess RE to the utility from residential consumers.

Globally, nearly 30% of the total energy consumed is attributed to domestic and commercial energy systems[17]. The residential sector accounts for 25% of energy consumption and 17% of global CO_2

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emissions[18], with an energy-saving potential of approximately 0.48 $\times 10^6$ ktoe[1] per annum[18]. Evidently, transitioning to Renewable Energy Systems (RES) in this sector has the potential to notably reduce its GHG emissions[6,15] leading to increased global interest in RE systems for domestic and commercial applications[17]. Electric grid-tied RE systems are most common in residential sectors throughout the world, as they not only increase the overall value of the home but also provide grid security against system shortfalls due to temporal fluctuations in RETs. These systems utilize the grid for storage, thus reducing the costs but they are not protected from grid downtimes and failures. As such, while stand-alone systems are costlier, they offer the advantage of energy storage allowing for 100% grid independence, thus providing a reliable solution for energy security and may be utilised in remote locations.

RET promotion in the power sector has been identified as one Nationally Appropriate Mitigation Action (NAMA) in TT's NDC implementation plan[6]. One of the guidelines for fiscal policy in actualizing VISION 2030 is investment in strategic infrastructure, whereby the GoRTT will establish a Green Infrastructure Fund (GIF) to support research and establishment of green infrastructures inclusive of affordable, greener housing[15]. While solar and wind technologies have notable potential due to their availability in TT, they each experience spatial and temporal variations, thus limiting their reliability for use in stand-alone systems[10,17]. As such, hybrid RE systems offer greater stability and have greater applicability since the compatibility of the systems offset their singular limitations[13]. This has resulted in increased global popularity particularly in developing countries with inadequate transmission infrastructure and significant remote areas. Hybrid solar-wind systems overcome the temporal variability associated with the supply of each resource, thus providing a more reliable, resilient system[10] that is well-suited to the climate in TT.

This study evaluates the potential of RE resources in TT by examining the performance of a hybrid-RE system in rural TT, and seeks to identify the role of RETs in the reduction of GHG emissions and the accomplishment of TT's NDCs. Mayaro, TT, is well known for its abundance of solar and wind energy resources and was thus selected as the site for the case study. The results of the 2011 population statistics collated by the Central Statistical Office (CSO)[19], for the region of Mayaro-Rio Claro identified the most common household type as a 2-bedroom (approximately 3,342 homes) followed by 3-bedroom (approximately 3,198 homes). However, 3-bedroom homes are more commonly found across TT, therefore, the study opted to focus on the energy consumption of 3-bedroom homes, with four inhabitants. Data acquisition required adherence of optimum ethical standards due to sensitive nature of the data required, which resulted in challenges in data retrieval. As such, the findings from Lunyu and Shuhan[20] where a comparison of the residential energy consumption profile of urban and rural areas in China found that the difference in geographic area was akin to econometric factors that could describe the heterogeneity in consumption levels, were applied. Thus, utility bills for 3-bedroom households in the Couva-Tabaquite-Talparo region, with identical consumption rates, standard of living, size, number of occupants, and geographic profiles were utilised due to easy accessibility. The research required the proposed hybrid-RE system model to be applied to similar households in TT, once the control factors were kept constant, therefore the utilization of data from another region did not impact the results and variable factors, such as availability of resource(s), were considered in the analysis.

To produce the model for evaluation, several simulation software such as HOMER Pro, Hybrid2, Hybrid Designer, and RETScreen were considered and evaluated. HOMER Pro, a simulation model that allows for the optimisation of micro-grid design for a multitude of scales, was selected due to its ability to consider multiple RE system components in hybrid micro-grid analysis[21]. The software also models the system performance according to the selected optimisation variable(s) for both grid-tied and off-grid (stand-alone) systems, while displaying the system's architecture. Moreover, it has embedded sensitivity analysis algorithms that allow for comparison and determination of the impact of specific input variables

[1] ktoe – kilotonne of oil equivalent; unit of energy equivalent to the approximate quantity of energy which can be extracted from one (1) tonne of crude oil

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on the system[22], and is thus widely utilised to evaluate the feasibility of grid-tied and stand-alone hybrid RE systems of various scales[23-25]. An analogous study utilizing HOMER Pro to determine the optimum system design for a stand-alone Hybrid Renewable Energy System (HRES) for similar residential houses in Marrakech, Morocco[26], showed that the optimum HRES configuration comprised a wind turbine, photovoltaic (PV) array, diesel generator, converters, and batteries which resulted in an LCOE of \$0.236 per kWh, the lowest value among all the hybrid systems designed[26]. When considering the renewable fraction (RF) parameter, the optimised hybrid-RE system yielded lower emissions whereas the configurations that included the diesel generator had increased CO_2 emissions despite being more economically feasible[26].

As TT endeavours to achieve its NDCs and mitigate climate change, the use of RE in residential power generation systems plays a vital role in the reduction of GHG emissions from the power generation sector[6,12]. A thorough review of the literature revealed scarce results in relation to appropriate RE system designs for rural residential applications across TT, thus cementing the need to address the gap in knowledge that exists. As such, this study seeks to address the knowledge gap by proposing the best suited RE system design, thereby contributing to substantial, data-driven evidence to support and advance the adoption of sustainable energy sources in rural TT.

2 MATERIALS AND METHODS

Fig. 1 outlines the general steps taken in the simulation and evaluation of the hybrid RE system using the HOMER Pro software.

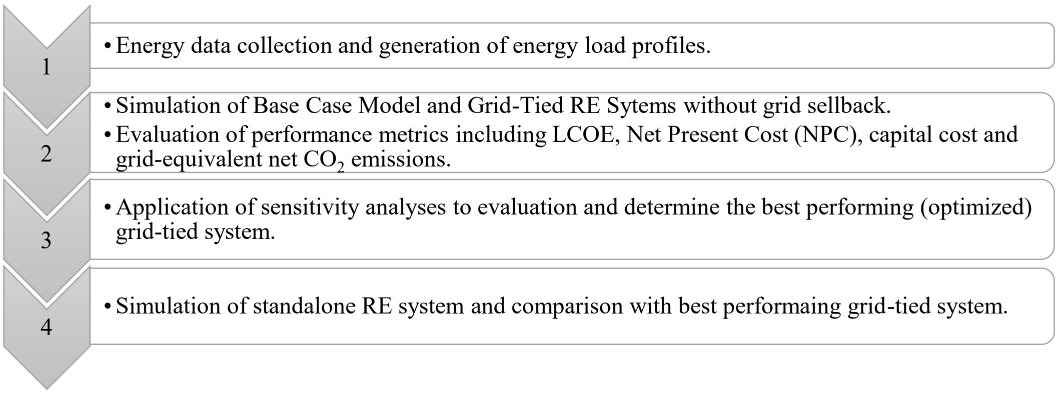

Fig. 1. Schematic of general steps in simulation and evaluation of the hybrid RE system.

2.1 Methodology

This expands on the strategy identified in Fig. 1 and follows a modified eight-step methodology adapted from similar studies by Seedath et al.[27], and Bentouba and Bourouis[10].

Step 1

a) Collect energy data

Electricity bills for a one-year period from January 2022 to December 2022 were collected from five 3-bedroom households with similar living standards and numbers of occupants, situated in the identified regional corporation. The data was used to calculate the average energy load rating per hour, the average monthly energy usage, and the average monthly peak demand of all five 3-bedroom households. For the average monthly peak demand, a power factor of 0.89 was applied to account for the efficiency of the

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present electrical system. This was estimated from meter readings where the ratio of the working power (kW) to apparent power (kVA) was determined.

b) Generate energy load profiles

Using the data-driven calculations in Step 1a, the energy load profiles were generated in Microsoft Excel, and the hourly energy requirements were entered into the HOMER Pro software and simulated with a 10% day-to-day and a 20% time-step variation to account for natural, random variability, and consideration of the error margin on the load profile, the latter of which was employed in similar studies. Daily, monthly, and yearly energy profiles were then generated.

c) Consideration of variations in electrical energy consumption

Steps 1b and 1c were repeated using the maximum monthly energy usage and peak demand of all households for the load ratings, instead of the average. This accounted for the possibility that the energy load consumption of the households was closer to the maximum monthly values.

Step 2

a) Simulate Base Case Model (grid-tied system)

The base case model was generated using the energy load profile, annual peak demand, and other specifications such as CO_2 emissions rate. The grid was identified as the power source using a feed-in tariff with net-metering disabled and a grid purchase price of $0.052 per kWh utilised.

b) Simulate grid-tied RE models

Other models were also simulated by adding and removing RE components from the base case model using the HOMER Pro software. Micro grid systems coupled with either PV, wind, or both (hybrid PV-Wind), were considered to determine the optimum design architecture that met the load requirement. To maintain the validity of the study, the system design remained the only variable in each simulation, and steps were taken to ensure that no component specifications were altered.

c) Evaluate all grid-tied systems using performance metrics

Selected performance metrics as highlighted in Fig. 2 were used to evaluate each grid-tied simulation. These included Levelised Cost of Electricity (LCOE), Net Present Cost (NPC), capital cost, operating cost, and grid-equivalent net carbon emissions.

Step 3: Perform sensitivity analyses to determine best performing grid-tied system architecture

Sensitivity analysis using grid purchase price was performed to determine the best performing system architecture. Upward variations of the grid purchase price, starting from the TT subsidised cost of $0.052 per kWh, were applied to determine the price point at which the RE system would become more lucrative than the grid. This was necessary because the current subsidised cost in TT resulted in the software identifying the base case as the most optimal system to meet the load requirement due to its affordability. Simulation results of minor increases from $0.052 to $0.10 per kWh showed no profitability in using RE. For larger increments from $0.50 per kWh, the simulation yielded desirable results; thus, increments of $0.50 were utilised to evaluate and identify the optimal system architecture based on the associated COE. Further sensitivity analyses were executed to assess the influence of each RE component on the system's performance and to evaluate the system's functionality under different scenarios, including unsubsidised grid purchase prices, regional and international purchase rates, and the possibility of grid sellback.

Step 4: Simulate a stand-alone RE system and compare with optimised grid-tied system architecture

For this model, the grid was removed as the power source, and a 12 V, 1 kWh lead-acid battery was added for energy storage to compare the parameters of an independent RE system to a grid-tied system for subsidised and unsubsidised grid purchase prices.

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2.2 Performance metrics

The simulated models were subjected to analyses based on the following performance metrics:

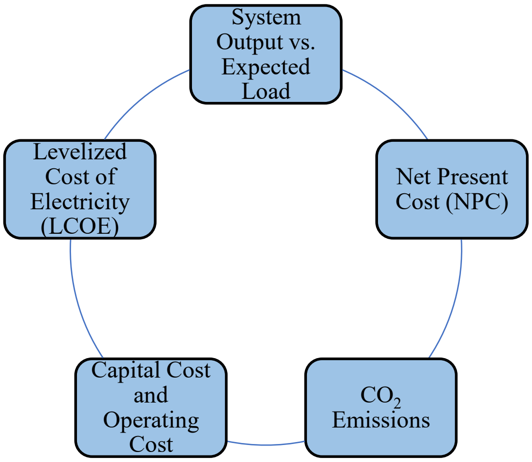

Fig. 2. Diagram highlighting performance metrics used in evaluating simulated systems.

2.3 Key input parameters/ variables

The following were key input parameters and variables used in the HOMER Pro software to simulate the models:

a) Weather data: location-specific wind and temperature data was obtained from National Aeronautics and Space Administration (NASA) Worldwide Energy Resources database, and the solar radiation data was obtained from National Renewable Energy Laboratory (NREL).

b) Component specifications: including equipment costs, operating and maintenance costs, equipment lifespan efficiencies.

c) Fuel Cost: current subsidised diesel price of \$0.651 per litre[28] and unsubsidised cost of \$0.78 per litre[29]. The world average cost is \$1.27 per litre[28].

d) Electricity Cost: average subsidised and unsubsidised rate in TT of \$0.052 per kWh[30], and \$0.12 per kWh[31] respectively; average Caribbean rate of \$0.35 per kWh[31]; and average world residential rate of \$0.158 per kWh[30].

e) Grid Feedback: sellback rate of \$0.086 per kWh (calculated as the mean of the subsidised and unsubsidised Cost of Electricity (COE) in TT).

f) Emissions Rate: 0.7 kg of CO_2 emissions for every kWh of electricity generated from natural gas in TT[27].

g) Capital Expenditure (CAPEX), Operational Expenditure (OPEX), and Lifetime of Components.

Table 1. Comparison of HOMER Pro simulation results for all evaluated systems

	CAPEX(US\$)	OPEX (\$/year)	LIFETIME (years)
Wind Turbine (Generic 3 kW)	18,000.00	180.00	20
PV Panel (Generic Flat Plate PV)	2,500.00	10.00	25
Converter	300.00	-	-
Battery (12 V, 1 kW Lead-Acid)	300.00	10.00	10

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3 RESULTS AND DISCUSSION

3.1 Collection of energy data and generation of energy load profiles

Steps 1a to 1c were followed to generate the load profile using the electricity bills collected from the target group within the Couva-Tabaquite-Talparo regional corporation. The data for monthly energy usage and peak demand were utilised to compute the total average energy consumption per hour, for a 24-hour period for weekdays, weekends and an average as shown in Fig. 3.

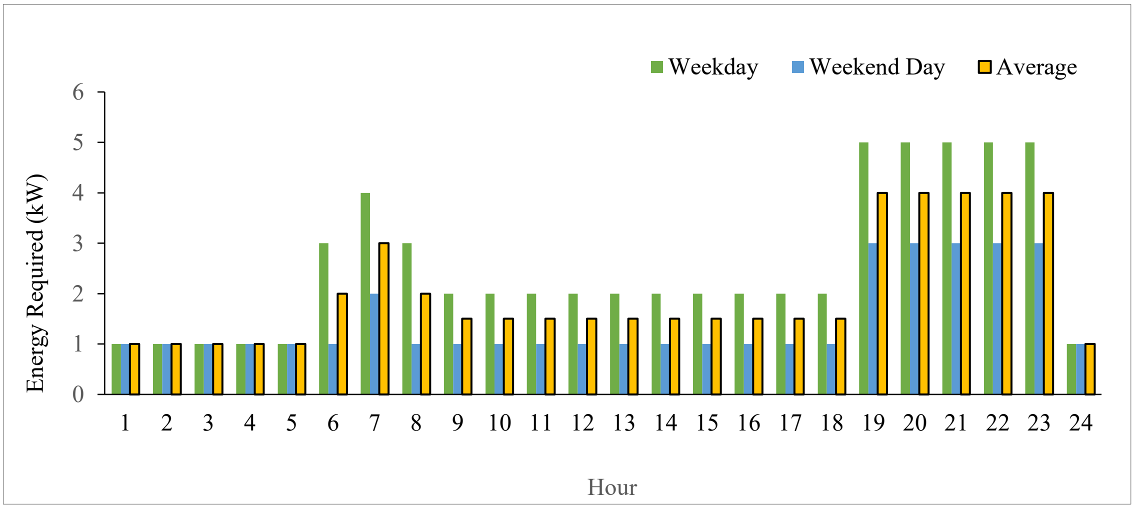

Fig. 3. A comparison of energy usage (kW) per hour of the day during the week and weekend.

A trend of higher energy use at home during weekdays in comparison to weekends, is apparent in Fig. 3. This anomaly may be attributed to the modification in work culture during the COVID-19 global pandemic that has resulted in most businesses and other entities adopting a work-from-home or blended approach, in an effort to reduce close contact among employees, resulting in increased energy use in homes during normal working hours. On the contrary, the lower energy consumption during weekends, may be attributed to families utilizing weekends to complete outdoor errands and for recreational activities.

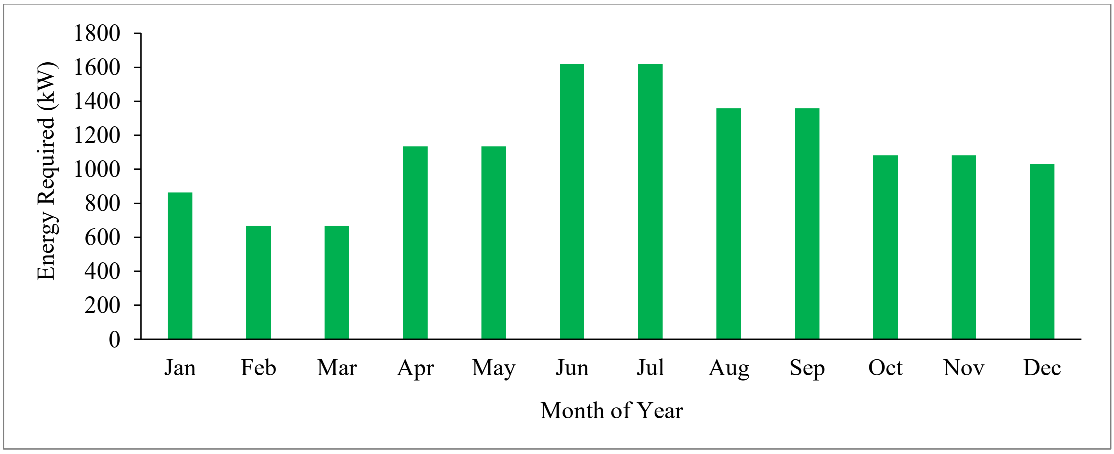

Fig. 4. Monthly energy requirements (kWh) of a 3-bedroom household during the year 2022.

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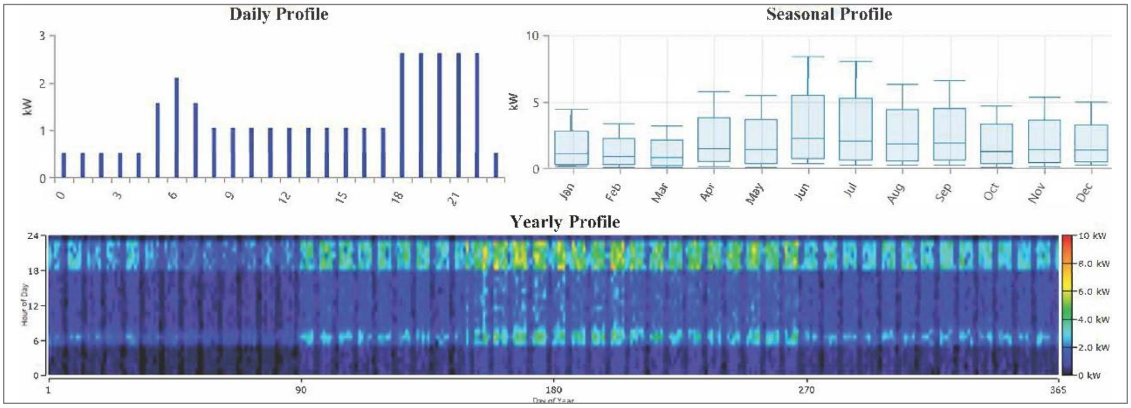
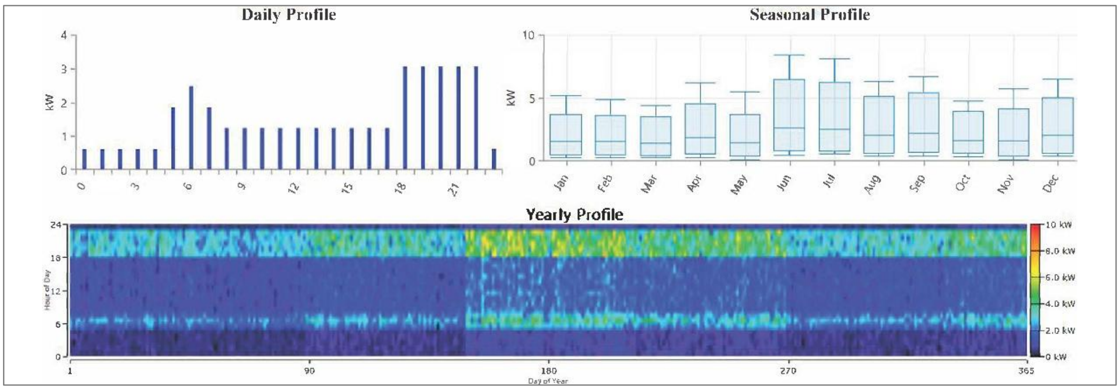
The load ratings for the 24-hour-period were then used to determine the total energy usage for each respective day, and the results were totalled to calculate the energy consumption for each month in the year 2022 as shown in Fig. 4.

Energy consumption was highest during the months of June and July (1620.75 kW per month) which may be attributed to the closure of educational institutions resulting in increased occupancy at home and increased energy use. However, a small decrease in consumption was noted in August, despite the closure of educational institutions. This may be due to the post-pandemic lifting of travel restrictions in TT in July 2021[32], resulting in increased travel during August.

The energy profiles generated by the HOMER Pro software following Steps 1b and 1c are shown in Fig. 5 (a) and (b). In this simulation, to account for variations in the monthly energy consumption rate, as highlighted in Step 1c of the methodology, the maximum monthly energy use was utilised instead of the average values, and the results are depicted in Fig. 5 (b).



(a)



(b)

Fig. 5. Energy load profiles generated using the a) average monthly energy consumption values, and b) maximum monthly energy consumption values from the dataset.

The results depicted in Fig. 5 reveal negligible differences in the load profiles generated using the average monthly energy consumption, and the maximum. However, the daily energy profile, similar to the manually plotted energy profile (Fig. 3) shows that the energy requirement was higher between 6 a.m. to 8 a.m., and after 7 p.m., synonymous with higher home occupancy rates. As with the previous simulation,

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the seasonal and yearly load profiles reflected a peak in energy usage during the months of June and July, however, there were notable increases from August to September, and decreases from February to March.

3.2 Simulations and evaluation of base case and RE Grid-tied Systems using performance metrics

Simulations of the base-case and grid-tied hybrid RE systems without grid sellback were generated using the HOMER Pro software in adherence with the desired component configurations as outlined in Steps 2a and 2b of the methodology and optimised to meet the input energy load requirements. The optimisation of the system considered the LCOE, NPC and grid equivalent net carbon emissions, supplemented by other parameters such as RE fraction, and initial and operating costs as noted in Step 2c of the methodology. The summarised results are shown in Table 2.

Table 2. Comparison of HOMER Pro simulation results for all evaluated systems

Metric	Base Case	Base Case Coupled with		
		PV System	Wind Turbine	Hybrid PV-Wind System
PV Capacity (kW)	-	0.003906	-	0.4375
Wind Capacity (kW)	-	-	3	6
Converter Capacity (kW)	-	0.001	-	0.271
Renewable Fraction (%)	0	0.100456	62.9	73.65
NPC ($)	2666.66	2674.777	23855.00	47650.00
LCOE ($/kWh)	0.052	0.054	0.449	0.897
Initial Capital Cost ($)	0	10.156	18000	37175
Operating Cost ($/year)	206.278	206.120	452.94	810.31
Net Emissions (kg CO_2/year)	2596.964	2594.355	963	684.00

A clear increase in RE fraction was noted in the RE system when compared with the base-case, indicative of a greater reliance on RE generation which would result in decreased CO_2 emissions, and creation of a more sustainable energy mix. The PV-only system required a minimal installed capacity of 0.003906 kW. This outcome reflected HOMER Pro's optimisation strategy, which prioritised economic feasibility by selecting components based primarily on NPC and LCOE. In the context of Trinidad and Tobago's heavily subsidised electricity rates, the grid remained the most cost-effective and dependable energy source. As a result, there was little financial incentive to invest in more expensive PV systems with high upfront costs and extended payback periods. As such, the model defaulted to the lowest feasible PV capacity necessary to meet the load without significantly increasing overall system cost. The NPC increased slightly to $2,674.777, and the LCOE to $0.054 per kWh, compared to the base case where the NPC was $2,666.66 and the LCOE was $0.052 per kWh.

In the comparative analysis of the three grid-tied RE systems, the hybrid system utilising 73.65% RE achieved a grid-equivalent net carbon emission reduction of 684 kg CO_2 per year which was equivalent to more than half the value for the base case (2,596.964 kg CO_2 per year). Notably, the NPC for the hybrid system was the highest, with a value of $47,650, owing to the cost associated with the incorporation of the wind turbine when compared with the NPC generated with the PV-converter system ($2,674.77). However, grid-equivalent net carbon emissions benefited greater from the utilisation of the wind turbine (963 kg CO_2 per year) in comparison with the PV-converter grid-tied configuration due to the notably higher value of 2,594.35 kg CO_2 per year recorded in the latter. Despite the environmental benefits due to the reduced CO_2 emissions, the associated LCOE of the RE systems containing wind turbines ($0.449 and $0.897 per kWh) was more than twice the value of the subsidised COE in the base case ($0.052 per kWh), due to the markedly larger initial cost for installing RE systems of this nature as well as higher operating costs. Therefore, it is evident that a balance between environmental impact and economic viability is crucial when evaluating RE system suitability.

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3.3 Sensitivity analysis to evaluate and recommend the Grid-tied System architecture

A sensitivity analysis was performed using the grid purchase price (GPP), increments of 0.5 were utilised to evaluate and identify the best performing grid-tied system architecture based on the associated COE, the results of which are depicted in

Table 3.

Table 3. Comparison of HOMER Pro simulation results for variations in grid purchase price

Grid Purchase Price ($/kWh)	PV Capacity (kW)	Wind Capacity (kW)	Converter Capacity (kW)	LCOE ($/kWh)	NPC ($)
0.052	-	-	-	0.052	2666.66
0.50	2.602	-	1.769	0.266	20,892.38
1.00	0.963	3	0.692	0.211	32,099.11
1.50	1.845	3	1.386	0.217	38,695.81
2.00	2.987	3	2.013	0.222	44,902.48

At a grid purchase price of $0.5 per kWh, the PV-converter system yielded the most favourable design configuration, with an associated LCOE of $0.266. However, when the grid purchase price was adjusted to $1.00 per kWh, the software proposed an optimal hybrid system that comprised a 3 kW wind turbine, and a 0.96 kWh PV system with a 0.69 kW converter. The associated LCOE for this system was even lower, at $0.211 per kWh. As such, appropriately paired hybrid RE systems yielded higher output in comparison with single technology RE systems and allowed for increased capacity of the grid to meet the growing energy demand[33] by selling any excess power generated. Thus, as stand-alone technologies, intermittent RE sources such as solar, and wind are limited, but when combined in hybrid systems, their reliability increases[34].

As seen in Fig. 6, the cash flow of the hybrid system was lower over the lifetime period when compared with the base case scenario. The intersection of both cumulative nominal cash flow trend lines indicated that the initial hybrid system cost was recovered after approximately six (6) years of use, making the system largely profitable. Thus, it was selected as the optimal grid-tied hybrid RE system architecture.

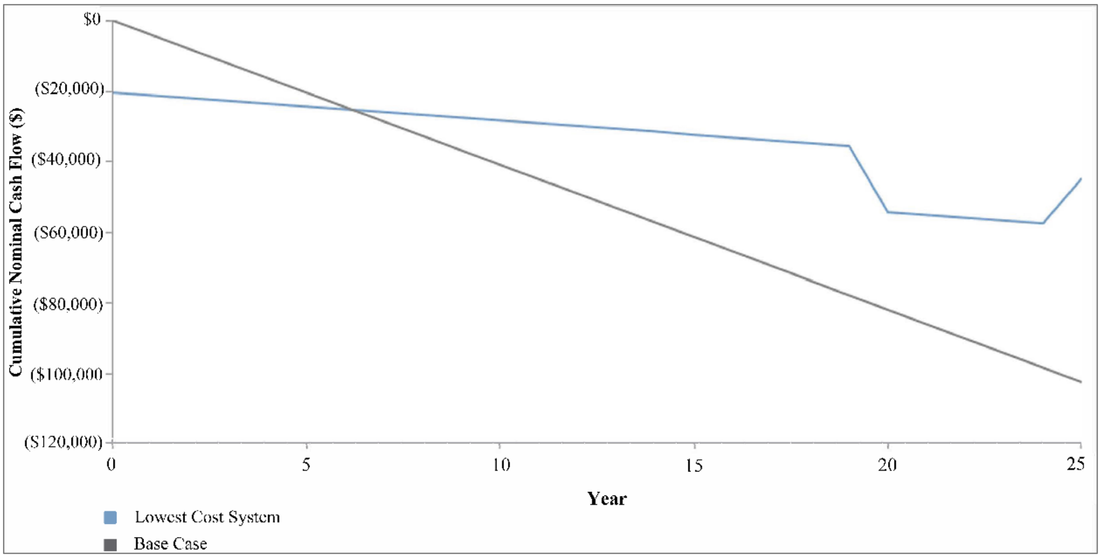

Fig. 6. Cumulative cash flow trend for best performing grid-tied system architecture.

Fig. 7 shows that the addition of the PV-converter and wind turbine increased the initial cost of the system, however, the NPC was reduced from $53,121 for the base case system to $33,406 for the proposed optimised system. This decrease may be attributed to the projected increased revenue generation from the

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hybrid system. As a result, the associated LCOE decreased from $1.00 per kWh to $0.211 with the hybrid system.

	Architecture								Cost	
					PV (kW)	G3	Grid (kW)	Converter (kW)	NPC ($)	Initial capital ($)
Base system							999,999		$53,121	$0.00
Proposed system					0.963	1	999,999	0.692	$33,406	$20,616

Fig. 7. Economics for the best performing grid-tied system architecture.

Fig. 8 shows the optimised grid-tied system architecture relied mostly on wind turbine energy each year, accounting for approximately 77.6% of the energy share. This accounted for most of the RE fraction associated with this hybrid system followed by 11.9% production by the PV component. The heavier reliance on energy produced by the wind turbine may be attributed to its larger capacity factor in comparison to the PV component, which allowed the system to operate at a higher capacity for more consistent electricity generation. Additionally, it may be likely that, at the location utilised for the software simulation, the wind resource was consistent, or that peak energy demand periods coincided with periods of high wind energy. Thus, the system recognised the benefit of prioritising wind energy to generate electricity more efficiently. The hub height of the wind turbine utilised in these simulations was 17 m while the NASA-derived wind speed data used by HOMER Pro assumed a reference height of 10 m.

Production	kWh/yr	%
Generic flat plate PV	1,461	11.9
Generic 3 kW	9,559	77.6
Grid Purchases	1,299	10.5
Total	12,318	100

Consumption	kWh/yr	%
AC Primary Load	4,109	33.6
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	8,118	66.4
Total	12,227	100

Quantity	kWh/yr	%
Excess Electricity	18.8	0.152
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	89.4	%
Max. Renew. Penetration	127	%

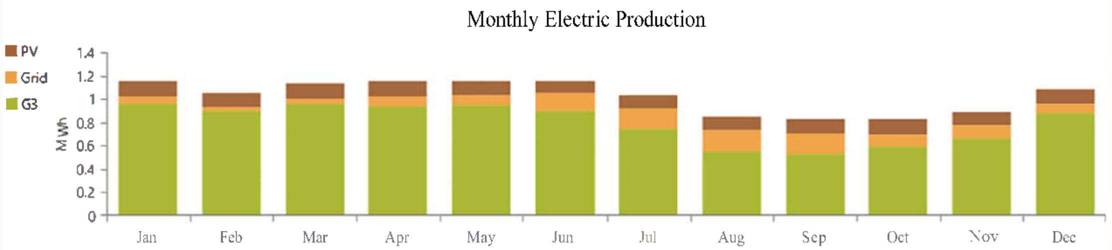

Fig. 8. Energy consumption scheme for the optimised grid-tied system architecture.

Given the high percentage of energy supplied by wind in the best performing grid-tied hybrid system, a comparative simulation was conducted utilising NASA-derived wind speed data, built-into HOMER Pro, for Couva-Tabaquite-Talparo at the same hub height. This simulation showed a similar result in which wind turbine energy accounted for approximately 78.2% of the energy share, as shown in Fig. 9, hence, justifying the feasibility of the hybrid system architecture under varying wind profiles.

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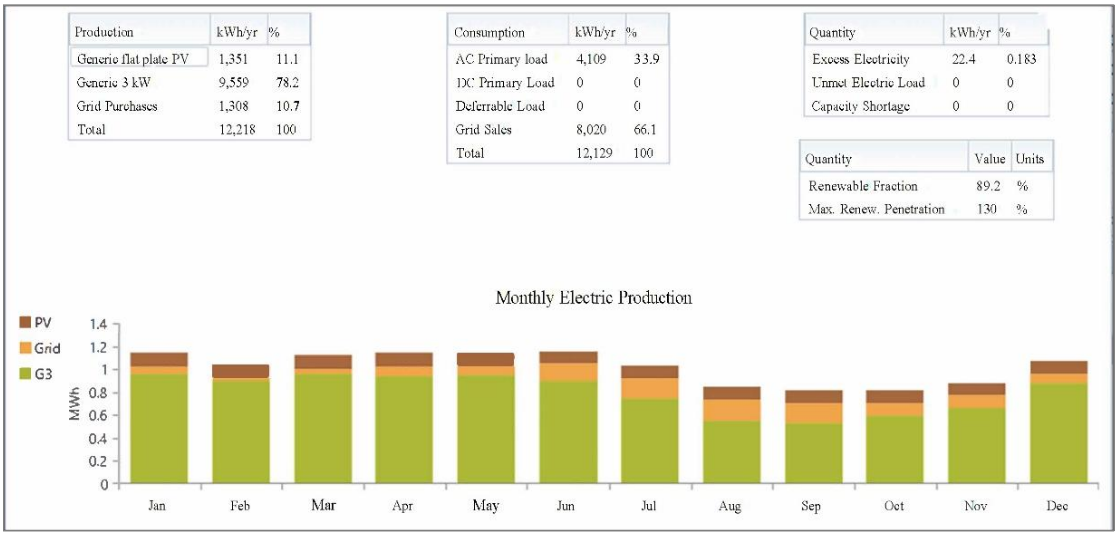

Fig. 9. Energy consumption scheme for the optimised grid-tied system architecture using wind dataset from Couva-Tabaquite-Talparo.

The rated PV capacity for the optimised grid-tied system architecture was 0.963 kW, with a PV penetration of 35.5%, which is reflective of the resultant energy consumption scheme projected for the hybrid system. Fig. 10 shows uniform PV power generation during sunlight hours between approximately 6 a.m. to 6 p.m., on an average day, throughout the year. The lack of power generation otherwise was attributed to the absence of the resource during those sunlight hours.

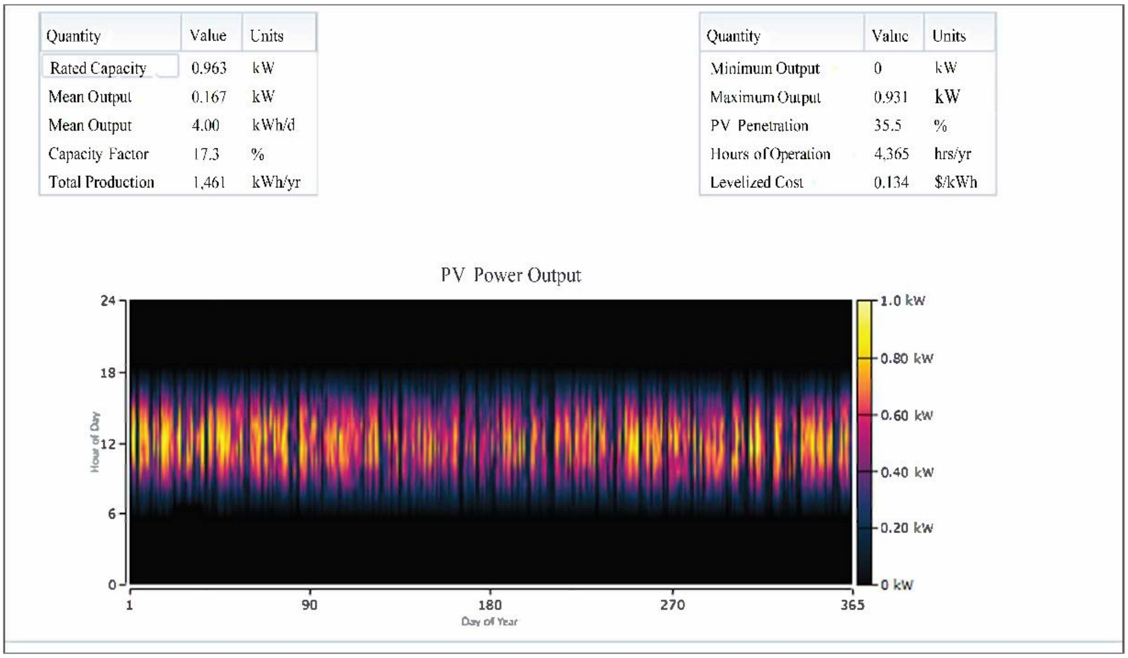

Fig. 10. PV energy scheme for optimised grid-tied system architecture.

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The total rated capacity of the wind turbine for the optimised grid-tied system architecture was 3 kW, with wind penetration of 233%. Fig.11 reflects this in the heavily fluctuated power generation by the wind turbine on an average day throughout the year due to variations in wind speed and direction. Unlike solar power generation, the availability, and quality, of wind power was unpredictable, as it fluctuated constantly. Parameters such as capacity factor, system design, components, maintenance, meteorological conditions, and extreme events can also affect the power generated by a wind turbine.

Quantity	Value	Units
Total Rated Capacity	3.00	kW
Mean Output	1.09	kW
Capacity Factor	36.4	%
Total Production	9,559	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	3.00	kW
Wind Penetration	233	%
Hours of Operation	7,817	hrs/yr
Levelized Cost	0.185	$/kWh

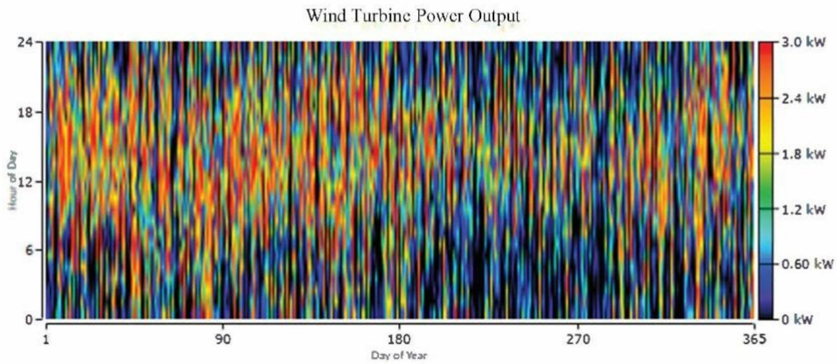

Fig. 11. Wind turbine energy scheme for optimised grid-tied system architecture.

Additional sensitivity analyses were executed to gauge the impact of individual RE components on system performance and to assess system functionality under different conditions, including unsubsidised grid purchase prices, regional and international purchase rates, and the option for grid sellback. A sensitivity analysis performed on the optimised grid-tied system showed that the wind turbine capacity has a much more significant impact on NPC, and LCOE, than PV capacity as shown in Fig.12.

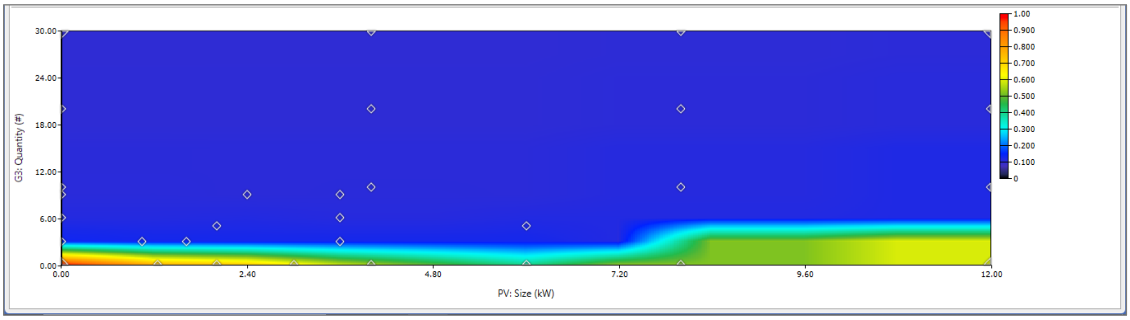

Fig. 12. Sensitivity analysis for optimised grid-tied system architecture.

Wind turbines operated at higher capacity factors because wind was available for a larger portion of the day in comparison to the highly variable solar irradiance that was only available during daylight hours. This resulted in greater electricity generation and improved financial performance of the system. Moreover, wind turbines have higher energy density than solar PV, due to the ability of wind to convert a larger

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quantity of kinetic energy in a given area, thus generating a larger power output. This also contributed to higher revenue potential. As such, wind turbines provide a better return in investment when electricity generation and revenue are considered, having a more significant effect on NPC and LCOE than the use of solar PV. Table 4 shows the results of a grid purchase price sensitivity analysis which compared the TT unsubsidised grid purchase price to the average regional and global rates for residential systems.

Table 4. Comparison of HOMER Pro grid price sensitivity analysis results without grid feedback

Metric	Grid Purchase Price/kWh		
	Unsubsidised ($0.12)	Average Regional/Caribbean ($0.35)	Average World Residential ($0.158)
PV Capacity (kW)	0.257	0.438	0.302
Wind Capacity (kW)	3	3	3
Converter Capacity (kW)	0.251	0.656	0.265
Renewable Fraction (%)	86.679	94.795	87.556
NPC ($)	30,069.36	48,602.12	26,632.78
LCOE ($/kW)	0.180	0.208	0.181
Initial Capital Cost ($)	18,421.67	37175	18,833.95
Operating Cost ($/year)	883.938	901.000	603.273
Net Emissions (kg CO_2 per year)	941.005	684.297	897.606

All simulations were evaluated without grid feedback and the sensitivity analysis showed that the Caribbean average rate of $0.35 per kWh, which was the most expensive of the three grid purchase prices evaluated, had the highest associated initial and operating costs, $37,175.00 and $901.00 per year respectively. This result was expected as higher grid purchase prices increased incentives to reduce grid reliance and increase RE installations. As such, the best performing grid-tied system comprised 0.438 kW of PVs and a 3 kW wind turbine, resulting in increased investment, operation, and maintenance costs. Consequently, this simulated scenario had the most significant RE penetration of 94.795%, resulting in the associated LCOE being the costliest of the three simulations at $0.208 per kWh and the grid equivalent net carbon emissions being the lowest at 684.297 kg CO_2 per year. Conversely, when the grid purchase price decreased, such as in the scenario with the unsubsidised grid purchase price of $0.12 per kWh, the software modelled an optimised grid-tied hybrid system configuration with smaller RE capacities. The modelled system comprised 0.257 kW PV and a 3 kW wind turbine with reduced initial and operating costs of $18,421.67 and $883.93 per year respectively, lower LCOE of $0.18 per kWh and increased carbon emissions of 941.005 kg CO_2 per year. A comparison of the simulation results utilising the unsubsidised grid purchase price and the average world residential price of $0.158 per kWh showed that the NPC associated with the former was valued at $30,069.36 compared to the latter valued at $26,632.78. This may be attributed to the inadequacy of the grid purchase price to offset the operating cost, resulting in a higher NPC.

Additionally, the optimised grid-tied system architecture was simulated with grid feedback, and no net metering, for both subsidised and unsubsidised grid purchase prices. For this sensitivity analysis the first grid sellback scenario (Case 1) utilised a sell back price of $0.086 per kWh, which was the mean of the subsidised and unsubsidised COE in TT. It should be noted that while it is unlikely for a utility company to engage in a situation where energy is purchased at a higher rate than it is sold; it is not entirely uncommon. This scenario can arise during periods of unexpectedly high or extreme demand whereby the demand for energy may exceed the utility's capacity to generate energy at a low rate as was seen during the Texas energy crisis in 2021[35]. Given the current heavily subsidised cost of electricity in TT and the high demand per household, a similar scenario is plausible and therefore should be considered. Thus, the simulations were performed with a higher grid sellback price to provide meaningful information to policy holders. For each subsequent simulation, the grid sellback price was increased upwards from the initial Case 1 price, and the evaluated metrics summarized is shown in Table 5.

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Table 5. Comparison of HOMER Pro grid sellback price sensitivity analysis results with net metering off for both subsidised and unsubsidised grid purchase price

Metric	Grid SellBack Price/kWh									
	Case 1: $0.086		Case 2: $0.09		Case 3				Case 4: $0.18	
					$0.10		$0.15			
	Grid Purchase Price: Subsidised (S) and Unsubsidised (US)									
	S	US	S	US	S	US	S	US	S	US
PV Capacity (kW)	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	12
Wind Capacity (kW)	6	6	6	6	6	6	6	6	6	3
Converter Capacity (kW)	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	9.10
Renewable Fraction (%)	94.80	94.80	94.80	94.80	94.80	94.80	94.80	94.80	94.80	96.12
NPC ($)	29,093	30,043	28,228	29,180	26,070	27,022	15,280	16,232	8,806	4,576
LCOE ($/kW)	0.108	0.112	0.105	0.109	0.097	0.100	0.057	0.060	0.033	0.013
Initial Capital Cost ($)	37,175	37,175	37,175	37,175	37,175	37,175	37,175	37,175	37,175	50,729
Operating Cost ($/year)	-625	-552	-692	-618	-859	-785	-1,694	-1,620	-2,194	-3,570
Net Emissions (kg CO_2/year)	684.30	684.30	684.30	684.30	684.30	684.30	684.30	684.30	684.30	682.54

Due to the small incremental changes in the grid sellback price, the capacities of the hybrid system components were consistent at 0.437 kW solar PV and 6 kW wind turbine and therefore, RE fraction and grid equivalent net carbon emissions remained unchanged at 94.795% and 684.297 kg CO_2 per year respectively. Notably, in all cases - both subsidised and unsubsidised grid purchase prices, the inclusion of grid sell back resulted in negative operating costs. This indicated that the hybrid system generated sufficient revenue to offset operation and maintenance expenses. This value decreased with increasing grid sellback price, emphasizing the importance of incentives such as grid sell back to offset the costs of RE systems and thus, increased its economic viability to promote more investments in such systems. Selling surplus electrical energy back to the grid is utilised globally to encourage homeowners to not only invest in RETs but also to be more aware and conservative in their energy consumption. A low operating cost also inadvertently decreased the associated NPC and LCOE of the system which was reflected from Case 1, to Case 4, as the grid sellback price was increased.

The most notable change in these metrics occurred in Case 4 where the grid sellback price was adjusted to $0.18 per kWh and the unsubsidised grid purchase price of $0.12 per kWh was applied. At this rate, the system can generate more revenue from excess electricity produced, offsetting the initial capital cost and reducing the payback period thereby increasing the attractiveness of investing in more RE. With the unsubsidised grid purchase price which was costlier than the subsidised grid purchase price of $0.052 per kWh, the incentive to decrease reliance on the grid and increase dependence on RETs existed. Thus, for Case 4, the software optimisation recommended an increase in the hybrid system size to include a larger solar PV capacity of 12 kW and a reduced wind turbine capacity of 3 kW to maximise excess generation and subsequent revenue earned from grid sellback. This larger dependence on RE (96.117%) also reduced the net CO_2 emissions of the grid-tied hybrid system to a value of 682.536 kg CO_2 per year. Therefore, it can be seen that increased grid sell back has the potential to not only enhance the economic viability of RE systems but also increase the feasibility of larger system configurations. Thus, it is evident that the option of grid sell back will increase the attractiveness of RE systems for residential use and therefore, TT should revise existing legislation to allow such.

3.4 Simulation of stand-alone system and comparison with optimised grid-tied system

Lastly, a stand-alone hybrid system was simulated and used for comparative analysis with the optimised grid-tied system using subsidised and unsubsidised grid purchase prices. The results from the

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best suited stand-alone system to supply the electric load input are summarised in Table 6. As expected, the stand-alone RE system has a RE fraction of 100% and 0 grid equivalent net carbon emissions. However, significant energy storage was required to ensure reliability of the system due to the intermittent nature of the energy resources. Hence, to meet the electric load requirement, the best performing stand-alone system comprised 2.22156 kW PV power, a 2.677 kW converter, 6 kW wind power, and 29 kW battery energy storage. The increased RE fraction coupled with the need for energy storage resulted in the need for significantly larger financial investments, and increased operation and maintenance costs, subsequently in a notably higher NPC ($71,676.53) and COE ($1.349 per kWh) when compared to the grid-tied system scenarios. Despite the increased initial expenditure due to the cost of system components, with optimum resource allocation based on the load demand, the system can have a significantly reduced operating cost, proving more cost-effective in the long-term[36] making it well suited for long-term energy security planning in TT.

Table 6. Comparison of results for simulated stand-alone and grid-tied hybrid systems with subsidised and unsubsidised grid purchase prices

Metric	Stand-Alone System	Grid-Tied System Purchase Price/kWh	
		Subsidised ($0.052)	Unsubsidised ($0.12)
PV Capacity (kW)	2.22156	0.438	0.438
Wind Capacity (kW)	6	6	6
Converter Capacity (kW)	2.677	0.271	0.271
Battery Capacity (kW)	29	-	-
Renewable Fraction (%)	100	94.9	94.795
NPC ($)	71,676.53	29,070.54	48,602.12
COE ($/(kW)	1.349	0.108	0.180
Initial Capital Cost ($)	51,057.01	37,175	37,175
Operating Cost ($/year)	1595.01	-626.915	883.938
Net Emissions (kg CO_2/year)	0	670.535	684.297

4 CONCLUSION

Ranked seventh in the world per capita for CO_2 emissions, it is imperative that TT reduces its carbon footprint and increases the country's resilience to climate change. Studies identified power generation as a major contributor to GHG emissions in TT and consequently, TT's intended NDC includes Carbon Reduction Strategies for this sector. Therefore, this study evaluated the role of RETs in reducing emissions in the residential power sector from BAU operations by the year 2030. A case study that examined the performance of various configurations of hybrid-RE systems for use in residential 3-bedroom homes in rural TT was conducted. Energy profile data was collected from five identical residential units and used to generate load profiles that were used to design different RE systems using the HOMER Pro software. Various economic and environmental analyses were then applied to the different models and their ability to reduce GHG emissions and the accomplishments of TT's NDCs were evaluated. The results showed that the best suited system for typical 3-bedroom residential units in TT was a grid-tied hybrid-RE system that utilises 94.9% RE, comprising a 3 kW wind turbine, and a 0.96 kW PV system with a 0.69 kW converter. This system has the potential to reduce emissions by 50% from the base case, which equates to 670.535 kg CO_2 per year, thus making this system well aligned with the objective outlined by TT to reduce GHG emissions. It is important to note that the subsidised cost of electricity in TT is a deterrent in implementation of RE systems due to the cost factor. With the removal of subsidies, the capital cost of the system will be lowered, and thus, financially more feasible. Moreover, current legislation in TT does not allow for grid-tied systems for residential purposes nor grid sellback options for independently produced power from the residential sector. Consequently, it is recommended that future work includes the application of this case study into a pilot project, particularly to showcase the importance of RETs in the achievement of TT's NDCs. Lastly, the authors strongly recommend that the findings from this study be utilised to inform policy development on the penetration of RETs in the residential electricity sector in TT and the option of grid sellback for excess power produced.

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CONFLICT OF INTEREST

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

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Visualisation: E. Cumberbatch
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Funding acquisition: N/A
Project administration: M.Boodhan, E. Cumberbatch, D. Boodlal, R. Maharaj

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