European Journal of Energy Research
Vol 5 | Issue 4 | August 2025
ISSN 2736-5506

RESEARCH ARTICLE

Renewable Energy Integration in Secondary Schools: A Case Study in Trinidad and Tobago

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ABSTRACT

Trinidad and Tobago (TT) must accelerate its transition to renewable energy (RE) to reduce greenhouse gas emissions, decrease its reliance on natural gas, and meet its Paris Agreement commitments. This study analyzed the energy load profile of a secondary school in TT to assess the feasibility and economic viability of integrating RE systems. Using the electricity consumption data, an hourly load profile was reconstructed and validated against an established model. This study evaluates various scenarios combining solar photovoltaic (PV) and wind energy systems under different electricity prices and configurations. The results showed that solar PV is the most promising option because of its strong alignment with the school's load profile, lower cost, and higher energy penetration. Net metering was found to be critical for economic viability, enabling the sale of excess electricity to the grid and offsetting the utility costs. Without it, renewable energy systems became feasible only at significantly higher electricity prices than the current subsidized rates. The optimal system design featured a 473.3 kW solar PV installation with net metering, achieving a payback period of nine years, an internal rate of return (IRR) of 9.9% and a levelized cost of electricity (LCOE) of US$0.064 per kWh. The system also reduced carbon emissions by 366,615 kgCO of e annually. These findings demonstrate the potential for solar PV in educational institutions, underscore the importance of supportive policies, such as feed-in tariffs, and provide actionable insights for policymakers and energy planners aiming to advance RE deployment in TT.

Keywords: HomerPro, load profile analysis, renewable energy, solar photovoltaic (PV) systems.

Submitted: July 10, 2025
Published: August 22, 2025

10.24018/ejenergy.2025.5.4.173

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1. Introduction

The urgent need to combat climate change and reduce greenhouse gas (GHG) emissions has gained significant global attention in recent years. The sixth assessment report from the Intergovernmental Panel on Climate Change (IPCC) emphasized the severe consequences of global warming and the pressing need for sustainable development. The Paris Agreement was introduced in 2015 to promote international collaboration and establish a sustainable pathway for reducing greenhouse gas emissions. TT, like other Small Island Developing States (SIDS) in the Caribbean, has ratified the agreement and committed to reducing its emissions through a Nationally Determined Contribution (NDC) and Renewable Energy (RE) target.

Despite these commitments, TT has struggled to meet its RE goals. The country relies heavily on natural gas for electricity generation, contributing approximately 99% of its utility provided electricity [1]. This reliance on natural gas has hindered the development of RE projects and poses challenges in achieving NDC targets for reducing greenhouse gas emissions. The government has also acknowledged the difficulty of promoting RE due to subsidized domestic energy prices, which makes it economically uncompetitive compared with natural gas [2].

The consequences of climate change, particularly for SIDS, such as TT, cannot be ignored. Rising sea levels, increased temperatures, and extreme weather events pose significant threats to vulnerable island nations. Therefore, it is crucial to accelerate the transition to RE and reduce a country's dependence on natural gas. By diversifying its energy sources, encouraging energy efficiency, and promoting RE solutions, TT can mitigate greenhouse gas emissions, reduce its reliance on natural gas, and alleviate the financial burden of subsidizing electricity [3].

Among the various RE options, solar and wind energy have emerged as promising choices for the TT. The country possesses abundant solar radiation, making solar photovoltaic (PV) systems an attractive solution for small- to large-scale installations [4]. Wind energy also shows potential, although large-scale deployments are generally required for optimal results. Resource assessments and economic evaluations are essential to determine the most suitable RE system for a specific facility or site. Simulation software tools, such as the Hybrid Optimization Model for Electric Renewable energy (HOMER), offer valuable insights into system performance, cost analysis, and optimization.

This study evaluates the technical and economic feasibility of incorporating a RE system, specifically solar PV and wind energy, into the energy infrastructure of a secondary school in the TT. Using actual electricity consumption data and the HOMER simulation software, various system configurations were analysed under different pricing and policy conditions. The goal is to identify an optimized system design that reduces emissions, minimizes costs, and informs national strategies for wider adoption of RE in the education sector.

2. Literature Review

2.1. The Global Push Towards RE

The increasing frequency and severity of climate change impacts have placed RE at the forefront of international development policies. IPCC's Sixth Assessment Report warns of escalating risks to ecosystems and human systems due to the continued reliance on fossil fuels [5]. The 2015 Paris Agreement was pivotal for global climate action, establishing NDCs to reduce greenhouse gas emissions.

Global efforts have seen strong growth in renewable electricity capacity, led by solar photovoltaic (PV), wind, and hydropower. According to the International Energy Agency [4], hydropower constitutes 63% of renewable electricity generation, with wind and solar accounting for growing shares owing to declining levelized costs of electricity (LCOE). Simulation tools such as HOMER Pro, iHOGA, and MATLAB Simulink are widely applied to analyse RE systems, optimize hybrid configurations, and model techno-economic feasibility [6], [7].

Studies by Shuaibu *et al*. [8] and Nesamalar *et al*. [9] successfully employed HOMER to evaluate microgrid and hybrid RE systems in off-grid or high-demand institutional settings. These methodologies support the current research's modelling approach, particularly in terms of scenario simulation, resource optimization, and economic sensitivity analysis.

2.2. Renewable Energy in the Caribbean and TT

Caribbean nations, classified as Small Island Developing States (SIDS), face unique vulnerabilities, including sea-level rise, extreme weather, and energy insecurity [10]. Despite their vast renewable potential, solar and wind penetration remains limited. Key barriers include fossil fuel dependency, weak regulatory frameworks, and artificially low energy prices, which make RE investment less attractive [3], [11].

TT, while the party to the Paris Agreement remains heavily reliant on natural gas, with over 99% of the electricity generated from fossil fuels [2]. National targets include a 10% RE share by 2021, which remains unmet. Subsidized electricity, priced at around US$0.05/kWh, further undermines the financial viability of RE projects [12]. Studies by Martinez and Hosein [13] and Seedath *et al*. [14] used an unsubsidized reference rate of US$0.12/kWh, similar to this thesis' methodology, to assess feasibility under more realistic cost conditions.

Recent government-led RE initiatives, including solar lighting at community centers and proposed utility-scale solar farms totalling 112 MW [15], mark early steps towards diversification. Existing small-scale systems include installations at the NP Preysal (100 kW), Savannah East POS (20 kW), and UTT campuses [14], [16]. Nonetheless, TT's regulatory instruments—the Trinidad and Tobago Electricity Commission (T&TEC) Act and RIC frameworks—still lack robust provisions for independent renewable producers, although reforms are underway [2], [17].

2.3. Integration of RE into Public Institutions and Schools

Schools and other public institutions present prime opportunities for small-scale RE deployments. Their fixed schedules and daytime energy use align well with the solar PV output, allowing for high self-consumption and minimal storage requirements [18], [19]. International research has shown that solar PV is economically and technically feasible in educational settings in both developed and developing regions [9], [20].

In TT, pilot installations such as UTT's 3 kW PV system and lighting solutions for 15 community centers have served as test cases. However, few publicly documented studies have addressed school-level RE optimization. The current study builds on this gap by applying HOMER simulations to model hourly load profiles, informed by Parker *et al*.'s [18] profile characterization techniques, and validated against empirical utility data.

The Ministry of Energy and Energy Industries [21] launched the Renewable Energy and Energy Efficiency Education Pilot Project to raise awareness of school-based RE systems. Aligning with this initiative, the current research proposes a scalable, cost-effective solar PV design for secondary schools, offering standardization potential across 134 public secondary schools [22].

Key findings from other studies using HOMER, such as Seedath *et al*. [14], White and Samikannu [7], and Shuaibu *et al*. [8], revealed that RE systems optimized for daytime loads, without battery storage, yield favorable LCOEs and GHG emission reductions when grid backup is available. This aligns with the findings of this study, which exclude battery storage due to cost inefficiencies and confirm that solar PV is the most viable RE solution for institutional applications in TT.

3. Methodology

The methodology employed a combination of empirical data collection and simulation-based modelling for the design and optimization of a hybrid RE system using HOMER software. The inputs included energy resources, technological and economic parameters, energy storage configurations, and system control strategies [23] (Figs. 1 and 2).

3.1. *Load Demand and Energy Model*

Hillview College, a government-assisted secondary school located in TT, was selected as the case study site for this research due to its typical weekday operational schedule, accessibility of electricity consumption data, and suitability for solar PV integration in line with national energy policy goals. An hourly load profile was constructed using the electricity consumption data provided by the T&TEC. Hillview College operates with three utility meters serving separate building clusters. Daily data were aggregated to determine total campus consumption during a typical school term week. Predictably, higher energy use occurred during school hours on weekdays, with lower stable consumption over weekends.

HOMER requires 'Yearly Load Data' with hourly resolution, divided by weekday and weekend profiles. Given the discrepancies in sampling intervals across meters, the average daily consumption for each was calculated and then combined to yield a representative weekday profile. The same approach was used for the weekends.

The observed data indicated a flat load profile during weekends and holidays, aligned with off-peak segments on weekdays. The load was then allocated accordingly, based on school schedules and empirical data, in a manner consistent with the profiles modelled by Parker *et al*. [18] (Fig. 3).

HOMER generates seasonal and annual demand simulations using this input. A variability of 20% was applied for daily fluctuations, and 15% for intraday load variability based on site observations.

The left panel shows a comparison between the modelled school profile (black line) and measured profiles from five other schools (coloured lines), as referenced from Parker *et al*. [18]. This highlights the typical diurnal energy demand pattern in schools, peaking during morning hours and tapering off in the evening. The alignment of the modelled profile with real-world data validates its reliability for simulation.

The right panel illustrates the variability introduced in the model. The black line represents the average modelled profile, while the coloured lines simulate ±15% fluctuations in hourly demand. These variability profiles were used in HOMER to capture intra-day demand shifts, enhancing the realism of the system simulations.

3.2. *Resource Assessment*

The location's resource data for solar and wind were obtained from the National Renewable Energy Laboratory (National Solar Radiation Database) and NASA Prediction of Worldwide Energy Resources (monthly average wind speed at 50 m above sea level over a 30-year period up to Dec 2013). These parameters were used as input parameters during the design and optimization processes. The annual average solar radiation is 4.97 kWh/m^2/day

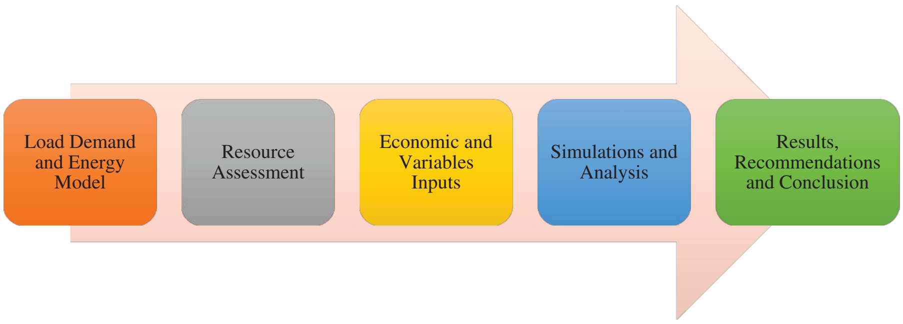

Fig. 1. An overview of the methods and process for design and optimisation.

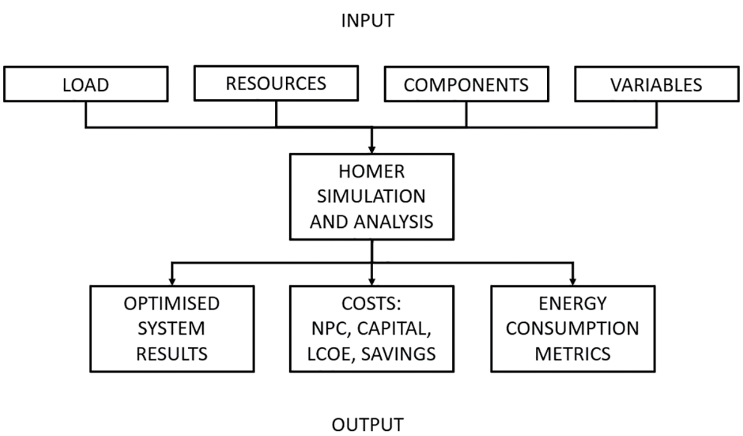

Fig. 2. Overview of design and simulation with HOMER software [23].

at the school's location. The annual monthly averages are shown in Fig. 3.

The annual average monthly wind speed is 7.72 m/s at the school's location. Wind resource data were captured using HOMER from the NASA Prediction of Worldwide Energy Resource (POWER) database (Fig. 4).

The monthly average temperature was also used within HOMER and gathered from NASA Prediction of Worldwide Energy Resource (POWER) database, using the monthly average air temperature over a 30-year period up to December 2013. The average annual temperature is 26.91°C, and the use of this feature for the calculation of the PV solar panels' temperature is a crucial aspect in modelling the PV system's efficiency (Fig. 5) [24].

3.3. Components and Variables Input

The costs provided by local and available suppliers were averaged for the components and used in the analyses. Other characteristics and economic parameters, including inflation adjustments and technology life span, are inputted based on the country and manufacturer's recommendations.

3.3.1. Grid

Hillview College falls under the T & T&TEC's Industrial Rate D1 category. The current subsidy rate is US$0.029/kWh, with a proposed increase to US$0.051/kWh. An unsubsidized rate of US$0.120/kWh was also considered, as well as a global average of US$0.190/kWh were also considered [25]. For net billing, a median rate of US$0.0745/kWh was assumed.

Grid reliability is high, with a SAIDI of 6.4–7.7 hours/year [26], justifying the exclusion of backup generators. GHG emissions were modelled using Ramsook *et al*. [27] with an emission factor of 560 gCO_2-e/kWh. The main grid characteristics, including industrial rates, selling rates, and emission factors, are summarized in Table I.

3.3.2. Components

3.3.2.1. PV System

CanadianSolar 325 W panels were modelled with 16.94% efficiency, a temperature coefficient of −0.41%/°C, and a 25-year lifespan. Including shipping and import costs, the capital cost was set at US$360/panel, equivalent to US$1,107.69/kW. A summary of the PV system characteristics used in the analysis is provided in Table II.

3.3.2.2. Inverter/Converter

A converter is required in electrical systems that includes both AC and DC equipment. In this study, the assumed efficiencies of the inverter and rectifier are the default generic values of 95% and 95%, respectively. The converter size is determined by either the minimum or maximum energy levels [28], and its costs are derived from current market value research at US$118.00 per kW. The converter specifications and costs are summarized in Table III.

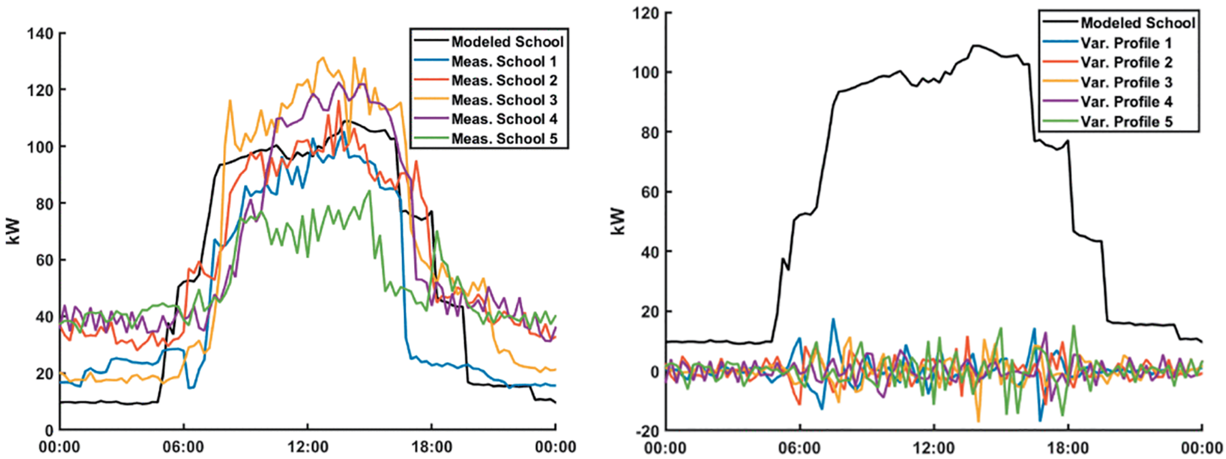

Fig. 3. Measured and modelled school building load profiles [18]: (left) Comparison between the modelled profile and data from five schools, (right) Variability profiles to simulate intraday fluctuations.

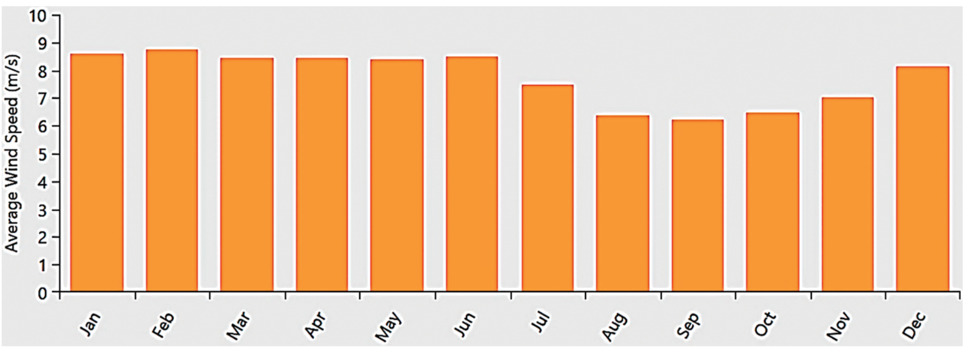

Fig. 4. Average monthly wind speed for Hillview College's location.

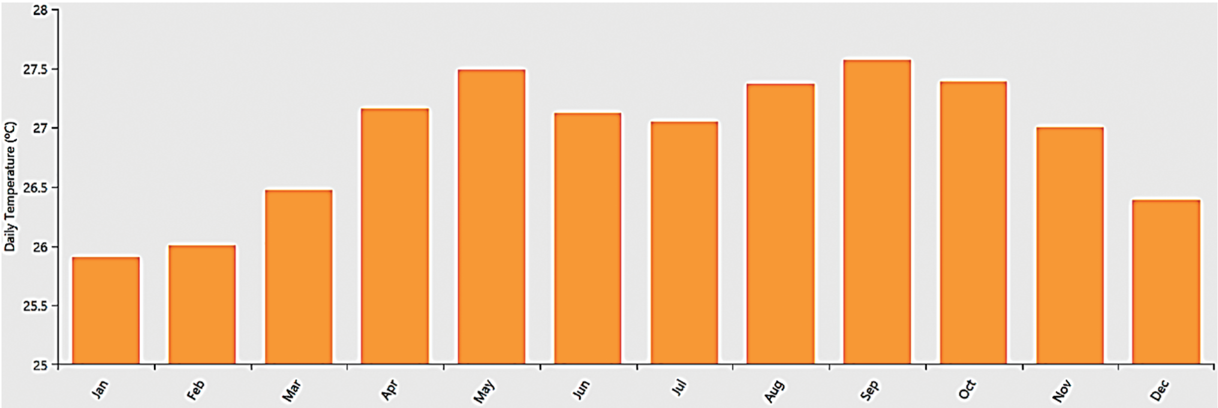

Fig. 5. Average monthly temperature at Hillview College's location.

TABLE I: Grid Characteristics Summary

Characteristic	Value		
Industrial rate (US$ per kWh)	Subsidized	Proposed increase	Estimated unsubsidized
	0.029	0.051	0.120
Grid selling rate (US$ per kWh)		0.0745	
Average world rate (US$ per kWh)		0.190	
Grid emission factor (gCO_2-e/kWh)		560	

TABLE II: PV System Characteristics Summary

Parameter	Value
Capital cost (US$/kW)	1,107.69
Replacement cost (US$/kW)	1,107.69
Operation & Maintenance cost (US$/kW/year)	30.77
Lifetime (years)	25
Efficiency (%)	16.94
Temperature coefficient (%/°C)	−0.41
Operating temperature (°C)	45
Derating factor (%)	86

TABLE III: Converter Characteristics Summary

Parameter	Value
Capital cost (US$/kW)	118.00
Replacement cost (US$/kW)	118.00
Lifetime (years)	15
Efficiency (%)	95

TABLE IV: Wind Turbine Characteristics Summary

Parameter	Value
Capital cost (US$/kW)	3921.57
Replacement cost (US$/kW)	3921.57
Operation & Maintenance cost (US$/wind turbine/year)	127.20
Lifetime (years)	20
Hub height (m)	15

3.3.2.3. Wind Turbine

A generic 3 kW wind turbine with a hub height of 15 m was modelled. The capital cost of US$3,921.57/kW, derived from Seedath *et al*. [14], reflects local importation and installation realities. A 20-year lifespan and annual O&M cost of US$127.20 were assumed. The wind turbine specifications are summarized in Table IV.

TABLE V: Battery Storage Characteristics Summary

Parameter	Value
Capital cost (US$/kWh)	600.00
Replacement cost (US$/kWh)	600.00
Operation & Maintenance cost (US$/wind turbine/year)	10.00
Lifetime (years)	10
Throughput (kWh)	1460.60
Roundtrip efficiency (%)	80
String size	3
String voltage (V)	36

3.3.2.4. Battery Storage

A 1 kWh lead acid battery with 80% round-trip efficiency and a 10-year lifespan was modelled. The battery was connected in a three-string configuration (36 V) to match the voltage of the PV system. The cost was set at US $ 600/kWh, with a throughput of 1,460.6 kWh and a minimum State of Charge (SOC) of 40%. The specifications of the battery storage system are summarized in Table V.

3.4. Simulations

The base-case scenario involved a grid-only supply. Successive simulations introduced renewable components and storage to compare the system architectures. A sensitivity analysis was conducted on grid power prices using HOMER's variable editor, examining the impact of current, proposed, and unsubsidized rates on system performance and feasibility.

3.5. Assumptions and Limitations

Several assumptions were made to facilitate the modelling and simulation processes in this study. Load profile reconstruction was based on aggregated daily consumption data provided by the utility company and hourly resolution was generated using standard school operational schedules and validated against Parker *et al*.'s model [18]. Solar irradiance and wind speed data were sourced from long-term NASA and NREL datasets, assuming consistency with present and near-future conditions. Equipment costs (PV panels, inverters, wind turbines and batteries) were based on current local market values, and no escalation or price fluctuation was considered over the project lifespan. Additionally, grid reliability was assumed to remain high, negating the need for backup generators.

Key limitations include the exclusion of real-time demand fluctuations and load variability that may arise from unforeseen operational changes or the addition of new electrical equipment. The modelling does not account for degradation of PV efficiency over time or the effects of soiling and maintenance on performance. Furthermore, while HOMER's optimization capabilities were used to simulate a wide range of system configurations, stochastic uncertainties in resource availability and market prices were not fully captured. These simplifications, while necessary for a tractable analysis, may lead to deviations when transitioning from simulation to real-world implementation. Future work should include real-time monitoring, field validation, and advanced uncertainty analysis to refine system performance projections.

4. Results and Discussion

4.1. Energy Load Profile

The hourly energy load profile was reconstructed based on utility-provided electricity consumption data for the school. The weekday and weekend calculated average daily load profile of the school's energy consumption per hour of the day is shown in Fig. 6.

The load profile of the school compared well with the model proposed by Parker *et al*. [18]. Fig. 6 compares the measured load profile of Hillview College with the modelled profile proposed by Parker *et al*. [18], showing strong agreement in weekday energy consumption peaks and lower weekend demand. This alignment validates the accuracy of the reconstructed load profiles used for system simulations.

As detailed in Tables VI and VII, weekday energy demand peaks between 7:00 AM and 3:00 PM, reflecting typical school operating hours, while weekend consumption remains consistently low. These insights confirm the suitability of solar PV systems, which align with daytime loads and reduce the need for storage during off-peak periods. The extracted and calculated data from the raw utility data for the school electricity consumption used to model the load profile are tabulated below (Fig. 7).

4.2. Simulated Scenarios

4.2.1. Base Model: Secondary School with Grid Connected

The base case, illustrated in Fig. 8 represents the current grid-only configuration. It demonstrates the highest annual emissions and energy costs, with no contribution from renewable sources, serving as a benchmark for evaluating RE alternatives. The first evaluated scenario was the base-case system, which is currently in operation with only a grid energy supply. The results show grid power equivalent emissions of 355,411 kgCO_2-e per year with 634,662 kWh of energy purchased.

In each of the other simulated cases with the electricity grid, the locally referenced electricity rates, unsubsidized, expected, and unsubsidized, will be compared along with the world average electricity rate and subsequently with the sensitivity variable editor with HOMER to find the tipping point at which RE is incorporated within the most optimized solution.

The grid price was then adjusted upwards from the subsidized current rate of US$0.010 per kWh to determine

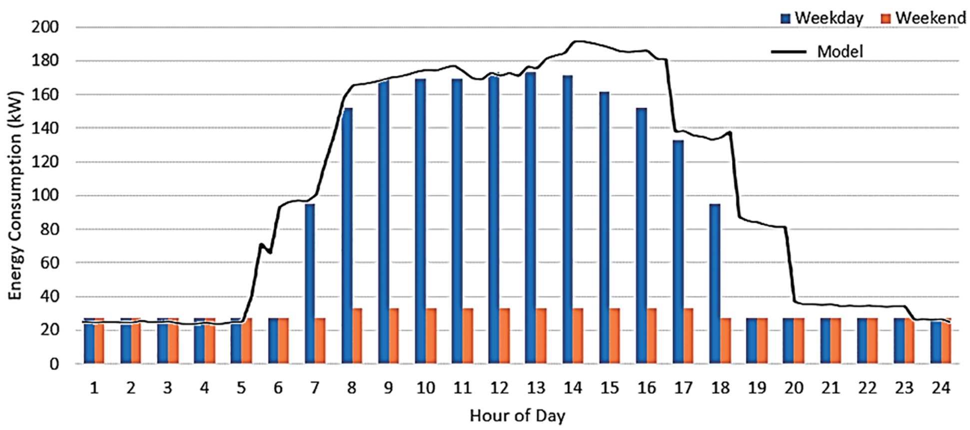

Fig. 6. Load profile of Hillview College compared with Parker *et al*. [18] model.

TABLE VI: Finalized Results from Utility Company Data from School's Electricity Meters

Day of week	Meter # Average kW per hour				Average daily total kWh
	9000785	9001208	9002384	Combined	Combined
Weekday	29.28	47.07	13.08	89.43	2146.32
Weekend	9.84	17.2	2.81	29.85	716.4

TABLE VII: Calculated and Modelled Load Profile for the Secondary School

Day hour	Weekday kWh	Weekend kWh
0	27.63	27.63
1	27.63	27.63
2	27.63	27.63
3	27.63	27.63
4	27.63	27.63
5	27.63	27.63
6	95.12	27.63
7	152.18	32.88
8	169.30	32.88
9	169.30	33.15
10	169.30	33.15
11	173.11	33.15
12	173.11	32.88
13	171.21	32.88
14	161.70	32.88
15	152.18	32.88
16	133.16	32.88
17	95.12	27.63
18	27.63	27.63
19	27.63	27.63
20	27.63	27.63
21	27.63	27.63
22	27.63	27.63

when the RE systems would begin to be included within the most optimized system and present an economically feasible option. In this scenario, the school relies solely on an electricity grid without renewable energy (RE) systems. The RE fraction is zero and the LCOE is equal to the grid price. This scenario served as the baseline for comparison.

4.2.2. Grid-PV Model: Secondary School with Grid and Solar PV Energy Systems Connected

Fig. 9 shows the integration of solar PV into the grid-connected system. Even with partial capacity, solar PV contributes over 50% of the system's energy, significantly reducing emissions and operating costs compared to the grid-only model. At the world average rate, the solar PV system is utilized with a 299-kW capacity and contributes a 55.3% RE fraction. The LCOE of this system is $ 0.135 per kWh.

The tipping point at which the system optimization began to include RE was established at a grid price of US$0.100 per kWh with 51.6 kW capacity and contributing a 11.2% RE fraction. The LCOE of this system was US$0.099 per kWh. Introducing solar PV systems to grid-connected schools leads to the introduction of RE into the system and a lower LCOE compared with the grid-only scenario. This indicates that solar PV systems can effectively contribute to reducing the school's dependence on the grid and lowering overall electricity costs. None of the winning architectures included batteries within the optimized system.

4.2.3. Grid-Wind Model: Secondary School with Grid and Wind Energy Systems Connected

As illustrated in Fig. 10 incorporating wind energy results in limited renewable contribution and only marginal improvements in cost and emissions. The high capital cost and variability of wind output make this option less favorable than solar PV. When the world average electricity grid rate is considered, at a grid rate of US$0.190 per kWh, the RE fraction is 26.2%, from the wind turbines, utilizing 17 3 kW wind turbines to give a 51 kW capacity wind energy system. The LCOE of this system was US$0.170 per kWh.

The tipping point at which the system optimization began to include RE was established at a grid price of US$0.120 per kWh with 21 kW capacity and contributing a 11.2% RE fraction. The LCOE of this system was US$0.119 per kWh. Although incorporating wind turbines into the system results in an RE contribution, the wind energy contribution is relatively low compared with solar PV in scenario 2. The LCOE is almost the same as the grid price, suggesting that wind energy systems may not be as cost-effective as solar PV systems.

4.2.4. Grid Hybrid PV-Wind Model: Secondary School with Grid, Solar PV and Wind Energy Systems Connected

Fig. 11 presents a hybrid model combining solar and wind. However, even in this configuration, solar remains the dominant contributor. The addition of wind offers modest performance gains but increases system complexity

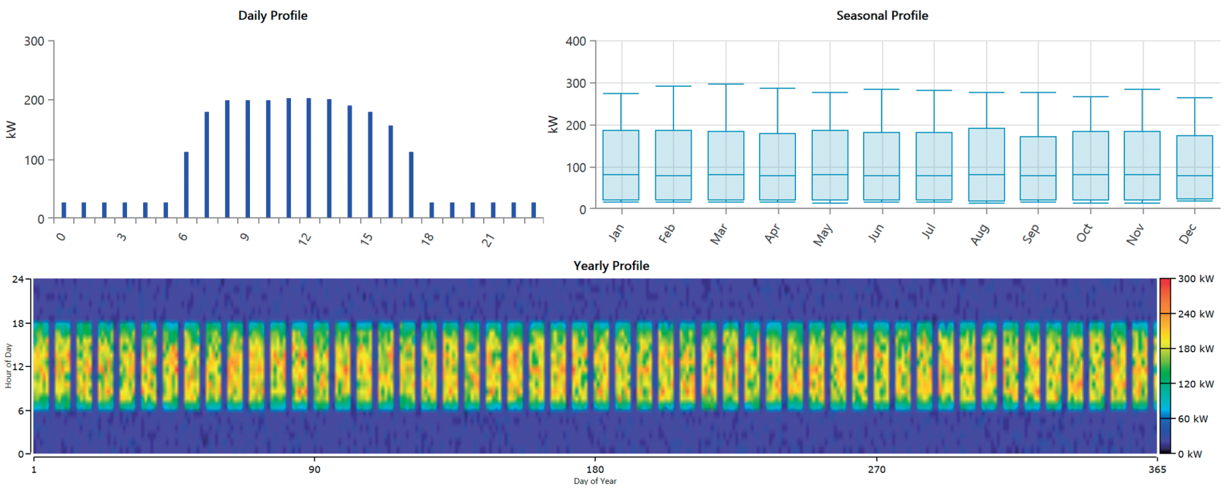

Fig. 7. Simulated energy load profile generated using HOMER.

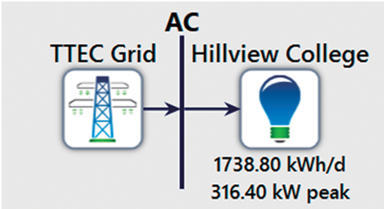

Fig. 8. Schematic of base model with grid connected system.

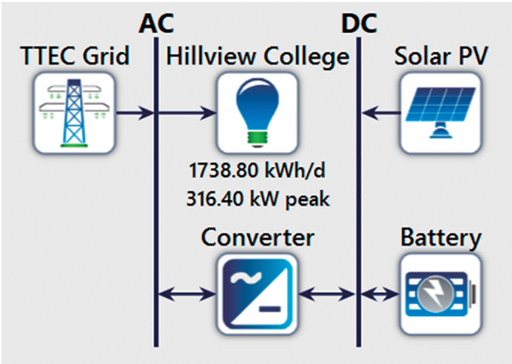

Fig. 9. Schematic of secondary school with grid and solar PV connected system.

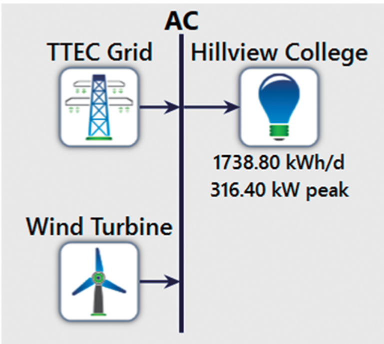

Fig. 10. Schematic of secondary school with grid and wind energy systems connected.

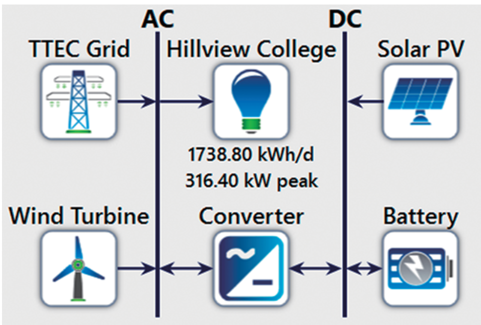

Fig. 11. Secondary school with grid, solar PV and wind energy systems connected.

and cost. The winning architecture of this optimized system at the world average electricity price has a RE fraction of 63.5%, with 77.4% of the RE fraction contributed by the solar PV system. The PV system contributes 57.0% of the system's yearly energy production, while the wind turbines contribute only 16.5%.

The tipping point at which the system optimization began to include RE was established at a grid price of US$0.100 per kWh with 51.6 kW capacity and contributing a 11.2% RE fraction. The LCOE of this system was

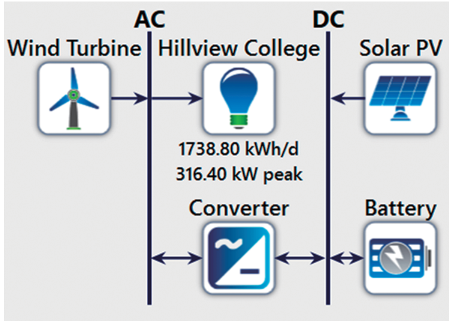

Fig. 12. Secondary school with solar PV and wind energy systems connected with battery.

US$0.0990 per kWh, similar to that of the solar PV system simulated in Scenario 2. Only solar PV was included in this optimized architecture, with wind energy being introduced when the evaluated grid price was increased to US$0.140 per kWh, introducing six 3 kW wind turbines (18 kW capacity), compared to the 199-kW solar PV capacity in that system.

This scenario combined solar PV and wind energy systems. The solar PV system dominates the RE fraction at 57%, and the LCOE remains similar to that of the grid-PV scenario, indicating that the inclusion of wind energy does not significantly impact the cost-effectiveness of the system. None of the winning architectures included batteries within the optimized system.

4.2.5. PV-Wind Model: Secondary School Solar PV and Wind Energy Systems Connected (No Grid)

In the standalone system shown in Fig. 12 both solar PV and wind are deployed without grid backup. While this configuration achieves 100% RE penetration, it is economically unviable due to the high LCOE and overbuilt capacity requirements. This scenario provides insight into a standalone fully RE system with no grid connection to understand how solar PV and wind turbines would compare and compete for energy production. The winning architecture has a considerably high LCOE of US$0.814 per kWh and a 1737 kW capacity solar PV system, in contrast to a 165-kW wind energy capacity system.

In this standalone RE system without a grid connection, the system has a considerably higher LCOE than the grid-connected scenarios. The wind energy system contributes 20.6% of the RE and has a significantly lower capacity than the solar PV system. This suggests that relying solely on wind energy is not economically viable without grid support, and that solar PV is a more favorable option.

4.2.6. Hybrid Selected Model: Secondary School with Grid and Selected RE Options Systems Connected

The selected RE model for the secondary school consisted of a grid-connected solar PV system, excluding both the battery storage and wind turbines. This configuration was identified as the most optimized solution based on the cost, performance, and alignment with the energy load profile of the school. A comparison of the results for Scenarios 1, 2, and 3 is presented in Table VIII.

Battery storage was not included in any of the optimized system architectures across the varying grid price

TABLE VIII: Comparison and Summary of Simulation Results for Scenarios 1,2, and 3

Metric	Scenario		
	1	2	3
	Grid Only	Grid-PV	Grid-Wind
Electricity price ($/kWh)	0.120	0.120	0.120
Solar PV capacity (kW)	–	135.9	–
Wind turbine capacity (kW)	–	–	21
NPC ($)	984,522	951,733	980,521
LCOE ($/kWh)	0.120	0.112	0.119
Operating cost ($/yr)	76,159	61,046	69,477
Renewable fraction (%)	0	28.5	11.2
Grid energy purchased (kWh)	634,662	471,241	564,170
Total system emissions (kgCO_2-e/yr)	355,411	263,895	315935.7
Emissions avoided (kgCO_2-e/yr)	0	91,516	39,475

TABLE IX: Comparison and Summary of Simulation Results for Scenario 4,5 & 6

Metric	Scenario		
	4	5	6
	Grid-PV-Wind	PV-Wind	Grid-PV Proposed
Electricity price ($/kWh)	0.120	0.120	0.140
Solar PV capacity (kW)	120.4	1,736	225.7
Wind turbine capacity (kW)	0	195	–
NPC ($)	951,424	6,677,224	1,062,651
LCOE ($/kWh)	0.113	0.814	0.118
Operating cost ($/yr)	62,479	187,070	61,382
Renewable fraction (%)	25.4	100	44.7
Grid energy purchased (kWh)	487,489	0	385,196
Total system emissions (kgCO_2-e/yr)	272,994	0	215,710
Emissions avoided (kgCO_2-e/yr)	82,417	355,411	139,701

scenarios. This exclusion is attributed to the high capital and operational costs of the batteries, which are economically outperformed by the utility grid as a backup for intermittent RE. The grid offers a more cost-effective and flexible alternative to batteries, particularly when considering the equivalent energy storage capacity and system integration complexity. The results for Scenarios 4, 5 and 6 are summarized in Table IX.

While battery storage was excluded from all optimized configurations in this study due to high capital costs and limited economic benefit under current conditions, its potential role in future energy systems should not be overlooked. With global trends indicating a steady decline in battery costs and increasing interest in dynamic electricity pricing models—such as time-of-use (TOU) tariffs—batteries may become more attractive in the medium to long term. Under TOU schemes, energy can be stored during off-peak periods when rates are lower and used or exported during peak periods, improving cost-effectiveness. Moreover, if grid reliability declines or demand charges are introduced, batteries could provide both resilience and economic value. As such, future studies should evaluate scenarios incorporating declining battery costs, TOU pricing, and storage incentives to reassess their viability in school-based renewable energy systems.

Solar PV systems consistently demonstrate the lowest associated grid price requirements for economic viability when compared to configurations incorporating wind energy, either independently or in hybrid systems. In all scenarios evaluated, up to the global average grid price, the contribution of wind energy to the total RE mix remained below 15%, highlighting its limited impact and cost inefficiency in the school context. Wind energy systems are characterized by relatively low renewable penetration, higher capital investment, and increased operation and maintenance costs per kilowatt of installed capacity.

Additionally, the school's load profile aligns well with solar energy production as peak energy demand occurs during daylight hours. This natural synchronization maximizes the utilization of solar energy throughout the day, further justifying the exclusion of wind turbines and batteries from system design.

Overall, the analysis supports the implementation of a standalone grid-connected solar PV system as the most effective and economically feasible RE solution for schools.

Fig. 13 presents the selected configuration: a grid-connected solar PV system without wind or batteries. This model offers the best balance of cost, performance, and feasibility for replication across secondary schools in TT. In this system, solar PV only (RE) is introduced into the winning system architecture at a grid price of US$0.140 per kWh. This grid price is above the referenced TT rates, including the unsubsidized electricity price. The respective LCOE is at US$0.118 per kWh with a 226-kW capacity solar PV system contributing a 44.7%

RE fraction. Considerations for introducing a solar PV system at an unsubsidized grid price would result in an increased LCOE.

At the world average electricity price of US$0.190 per kWh, the respective LCOE is at US$0.135 per kWh with a 299-kW capacity solar PV system contributing a 55.3% RE fraction. The resulting GHG emissions from this system are 184,836 $kgCO_2$-e per year, representing a 48.0% reduction in GHG emissions from the base case.

Without grid sellback, this result highlights an optimized design with the proposed system to be economically unfavourable at the unsubsidized electricity costs. When evaluated, the system was unable to achieve a payback within its lifetime nor presented an LCOE lower than the grid purchase price.

Another design consideration is to restrict the proposed RE system to a defined power capacity. This would allow for standardization of such a system across secondary schools with a template design and solution that could provide an overall LCOE, contribute to GHG emission reductions, and provide an Internal rate of return (IRR) towards a payback period within the lifespan of the system. HOMER's 'Search Space' function allows for the evaluation of components within a specific sizing to be considered in each optimization case. This can be used to force optimization to consider how a system with a specific power capacity will perform against the load requirements. The winning architecture for a 100 kW solar PV system, at the unsubsidized grid price of US$0.120 per kWh, contributes a renewable fraction of 21.3%. Table X summarizes the results of the system.

Although the overall RE penetration of such a system is considerably small at 21.3%, the system has a payback

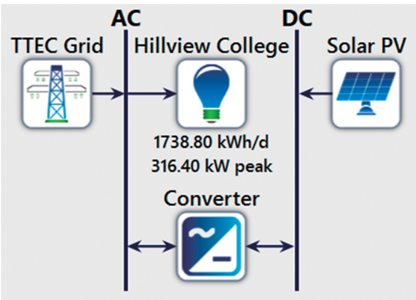

Fig. 13. Secondary school with proposed RE system, solar PV, without wind and batteries.

TABLE X: Proposed RE System Restricted to 100 kW Capacity

Metric	Scenario
	Grid- 100 kW PV
Electricity price ($/kWh)	0.120
Solar PV capacity (kW)	100
NPC ($)	951,925
LCOE ($/kWh)	0.113
Operating cost ($/yr)	664,412
Renewable fraction (%)	21.3
Grid energy purchased (kWh)	487,489
Solar PV energy produced (kWh)	509,248
Total system emissions ($kgCO_2$-e/yr)	285,179
Emissions avoided ($kgCO_2$-e/yr)	70,232

of 10 years with an IRR of 8.6%. With a smaller solar PV capacity, the capital expenditure was US$119,235, which is considerably lower than the optimized solutions presented for the proposed system, which restricts the RE capacity. Exploring the impact of restricting the RE system to a defined power capacity of 100 kW, although the overall RE fraction is relatively small, this restriction allows for standardization and cost reduction. The payback period of the system is 10 years, indicating a reasonable return on investment within the lifespan of the system.

4.3. Grid Feedback

If the grid sellback is included in the selected RE system, at the median electricity rate between the subsidized and unsubsidized electricity costs, RE (solar PV only) is introduced into the system at a grid price of US$0.110 per kWh. The respective LCOE is at US$0.103 per kWh, with a 280-kW capacity solar PV system contributing a 53% RE fraction.

A sensitivity analysis was performed, where a range of sellback prices was evaluated along with varied electricity prices within US$0.010 per kWh increments. At the actual subsidized grid price, no practical sellback price allows for the introduction of RE into the system. Considering unsubsidized grid costs, US$0.120 per kWh, grid feedback included a sellback price at the median electricity rate between the subsidized and unsubsidized electricity costs, US$0.0745 per kWh, the respective LCOE is at US$0.0876 per kWh with a 352-kW capacity solar PV system contributing a 61.9% RE fraction. This price pair provides a payback period of 10 years and an IRR of 8.2%.

Fig. 14 illustrates cash flow trends for systems under unsubsidized electricity costs with grid sellback. The chart shows steady improvement in cumulative cash flow as PV capacity increases, with economic breakeven points occurring earlier when sellback is permitted. The solar PV system begins to contribute more energy to the system if grid feedback is included, as it contributes towards a more economical solution to sell excess power to the grid. At a sellback rate of US$0.090 per kWh, with the assumed unsubsidised electricity purchase price, the system begins to present a net negative operating cost per year and boasts a LCOE at US$0.0327 per kWh.

In a Net Billing scenario, where the price of electricity is assumed to be the unsubsidized rate, US$0.120 per kWh, and with a net excess price of US$0.0745 per kWh, the winning optimized system includes a 473-kW solar PV capacity contributing a 72.2% RE fraction. A payback period of 9.0 years with a 9.9% IRR and an LCOE of US$0.0643 per kWh is determined by the system. In these scenarios, excess electricity is sold to the grid at US$0.0745 per kWh. Any increase in the selling price would lead to more economically advantageous options with greater total cash flow throughout the lifespan of the system. With net metering allowing for the contribution of excess electricity to the grid, such a system would be profitable and contribute to net carbon emissions reduction as it would replace and supplement conventional grid energy.

In a scenario where we reconsider wind energy and include the option in the RE system, HOMER optimizes each net metering scenario with wind energy excluded, with matching winning architecture from the proposed system. This further supports the decision of excluding wind energy from the proposed RE system.

In Fig. 15 the introduction of net metering dramatically improves system performance, resulting in significantly higher cash flow and shorter payback periods. This reinforces the value of grid interconnection policies that allow excess generation to be compensated.

Table XI summarizes key performance metrics for net metering scenarios. Systems with higher sellback rates achieved the lowest LCOEs (as low as US$0.002/kWh) and shortest payback periods (as low as 5.4 years), highlighting the importance of favorable net metering rates in enabling economic feasibility. Net metering scenarios allow for the offset of energy consumption from the energy generated by the solar PV system. Grid feedback with net metering significantly reduces the LCOE and operating costs. The renewable fraction is also higher as net metering relies more heavily on the larger solar PV capacity, which generates a higher proportion of RE, as these scenarios benefit from selling excess energy back to the grid. In contrast, in scenarios without net metering, the system relies more on the grid for energy supply. Additionally, in the scenarios with net metering, excess energy is sold back to the grid, resulting in a higher amount of energy being sold compared to the scenarios without net metering. Overall, the trends indicate that the net metering scenarios offer a higher renewable fraction, lower LCOE and operating costs, and lend economic feasibility to the proposed RE system.

The economic favourability of RE systems increases with the inclusion of grid sellbacks or net metering. Net metering scenarios demonstrate the profitability and carbon emission reduction potential of RE systems when excess electricity can contribute to the grid.

Considering the effect of net metering with respect to increasing economic favourability, we can also simulate and compare the effect it presents with a 100-kW capacity proposed RE system for the unsubsidized electricity costs, as seen in Table XII.

Table XII analyses a standardized 100 kW system under various net metering conditions. Despite lower RE penetration, the system achieves respectable IRRs and payback periods under higher sellback conditions. However, limited export capacity reduces its cost-effectiveness compared to larger systems. These results also present an interesting view of the capacity of the system and provide insight into how an inadequately sized RE system for the proposed solution would be performed. The system is able to slightly reduce the LCOE compared to the grid power price; however, even with net metering, it is unable to sufficiently produce excess electricity to assist in reducing the overall operating costs. The system can provide payback within a 9-year period. Regardless of the sellback price, it has a small impact on the economics of the system. Without a considerable portion of excess energy to be sold to the grid, sellback has a diminished effect overall.

In the simulated scenarios, the renewable fraction of each system was proportional to the GHG emissions avoided by using RE. With grid sellback included, excess energy can be sold to the grid and provides a GHG emissions offset to the grid power that it replaces.

The benefit of net metering allows an RE system with excess energy production to offset the costs by selling energy to the grid. The net metering winning architecture from the proposed solar PV system, where the unsubsidized electricity cost of US$0.120 per kWh was paired with a selling rate of US$0.0745 per kWh, is shown in Fig. 16.

Fig. 16 provides a comparative overview of the current and proposed systems, visually emphasizing the performance improvements achieved through the adoption of grid-connected solar PV with net metering. The recommended system yields the highest renewable fraction, lowest operating cost, and the greatest emissions offset—demonstrating its potential for national replication in the education sector. This study evaluated the energy load profile of a secondary school and explored various renewable energy (RE) configurations to optimize energy consumption. Through the reconstruction of an hourly load profile based on utility-provided data validated against the Parker *et al*. [18] model, the analysis offers a reliable baseline for

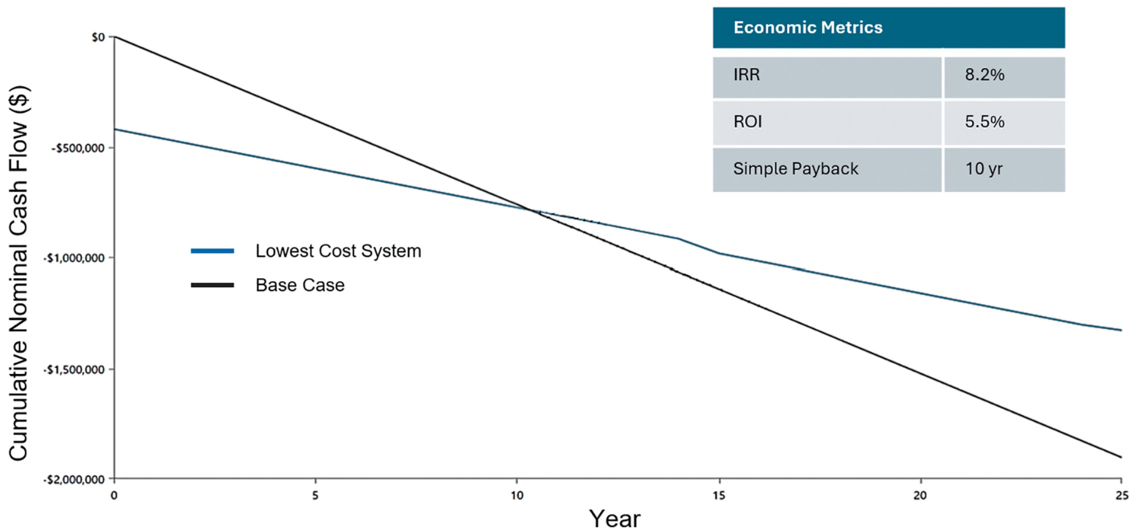

Fig. 14. Cash flow trend considering unsubsidized grid costs with grid sellback.

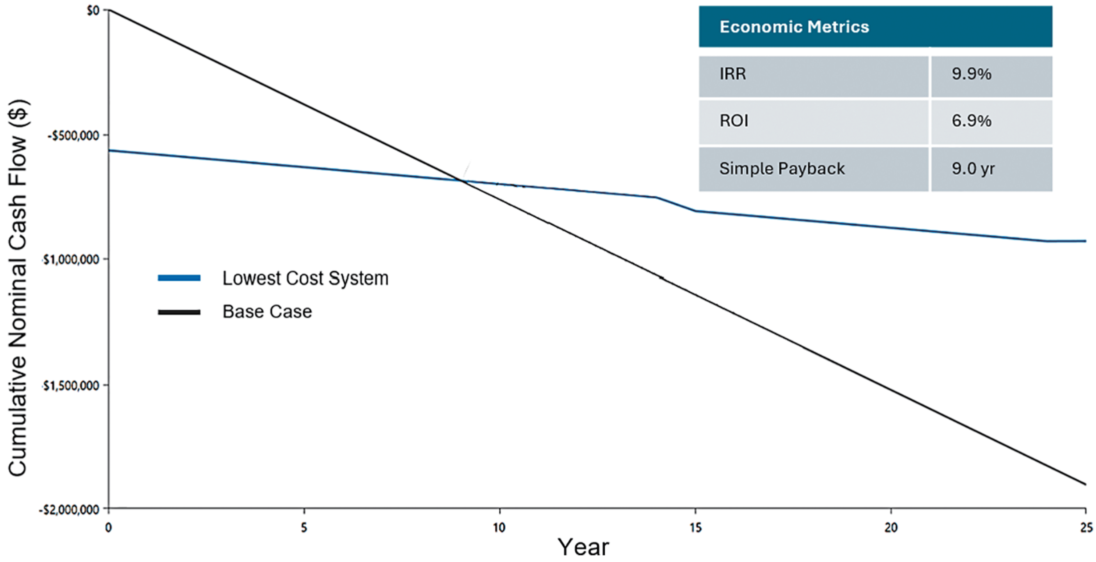

Fig. 15. Cash flow trend considering unsubsidized grid costs with net metering.

TABLE XI: Net Metering with Optimised Solutions Considering Feasible Price Pair

Metric	Net metering scenario			
Electricity price ($/kWh)	0.120	0.120	0.190	0.190
Sellback price (kW)	0.0745	0.120	0.0745	0.120
Solar PV capacity (kW)	473.3	1,739	496.2	1739
NPC ($)	754,348	77,078	756,912	77,078
LCOE ($/kWh)	0.064	0.002	0.063	0.002
Operating cost ($/yr)	14,572	−154,858	12,776	−154,858
Renewable fraction (%)	72.1	94.2	73.5	94.2
Grid energy purchased (kWh)	252,634.2	148,053.9	246,175.7	148,053.9
Grid energy sold (kWh)	272,640.6	1,918,349	296,066.7	1,918,349
Payback (yr)	9.0	8.8	5.4	7.4
IRR (%)	9.9	10.1	18.0	12.6
Total system emissions ($kgCO_2$-e/yr)	141,475	82,910	137,858	82,910
Emissions avoided ($kgCO_2$-e/yr)	213,936	272,501	217,553	272,501
Emissions offset ($kgCO_2$-e/yr)	152,679	1,074,275	165,797	1,074,275

TABLE XII: Net Metering with a 100 kW Capacity Proposed RE System

Metric	Net metering scenario–100 kW RE system			
Electricity price ($/kWh)	0.120	0.120	0.190	0.190
Sellback price (kW)	0.0745	0.120	0.0745	0.120
Solar PV capacity (kW)	100	100	100	100
NPC ($)	932,371	932,371	1,381,524	1,381,524
LCOE ($/kWh)	0.111	0.111	0.165	0.165
Operating cost ($/yr)	62,877	62,877	97,576	97,576
Renewable fraction (%)	21.4	21.4	21.4	21.4
Grid energy purchased (kWh)	508,999	508,999	508,748	508,748
Grid energy sold (kWh)	12,609	12,609	12,696	12,696
Payback (yr)	8.8	8.8	5.2	5.2
IRR (%)	10	10	19	19
Total system emissions ($kgCO_2$-e/yr)	285,040	285,040	284,899	284,899
Emissions avoided ($kgCO_2$-e/yr)	70,371	70,371	71,512	71,512
Emissions offset ($kgCO_2$-e/yr)	7061	7061	7110	7110

system simulation. The findings revealed that the school's energy consumption peaks during daytime hours, which aligns well with the solar energy production patterns, thereby enhancing the viability of solar PV systems.

Multiple scenarios were simulated to compare the performance and economic feasibility of RE systems, including standalone solar PV, wind energy, hybrid PV-wind systems, and systems with battery storage. The

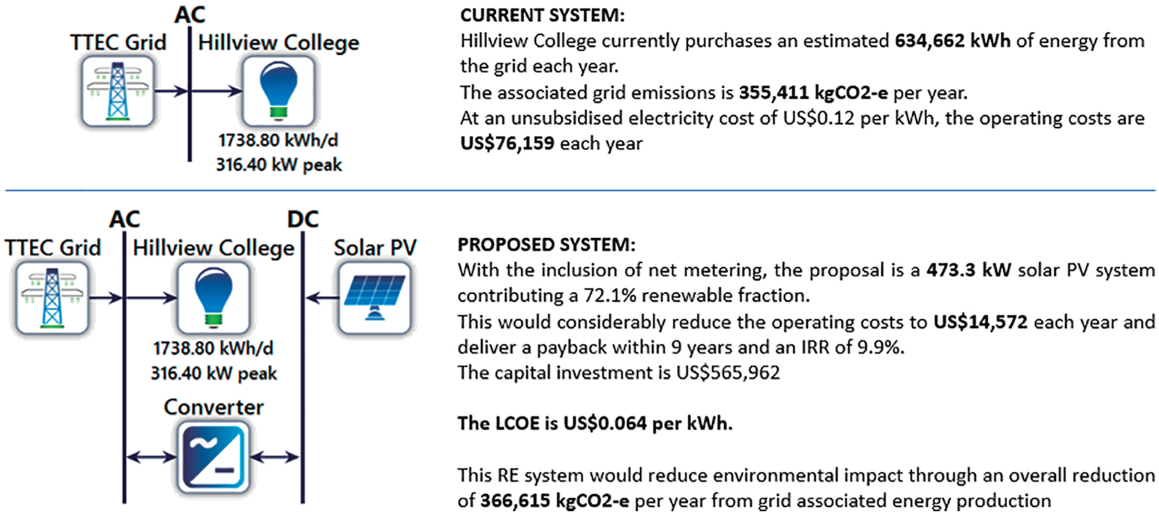

Fig. 16. Comparison summary of the current and proposed system winning architecture.

base model, which represents the grid-only supply at an assumed unsubsidized electricity rate, served as a reference for comparison. It was found that RE investments are currently uneconomical under TT's low electricity tariffs.

Among the scenarios, the standalone solar PV systems consistently outperformed the other configurations. The LCOE for the PV-only system was 5.9% lower than that of the hybrid alternatives and had a higher renewable penetration at lower capital and operational costs. Wind energy, on the other hand, had higher costs and lower system contributions, becoming economically viable only at a grid price of US$0.120 per kWh, compared to US$0.100 per kWh for solar PV. Battery storage was excluded from the optimal configurations because of its high cost and limited economic value when grid power is available as a backup.

Net metering has emerged as a critical enabler for economic viability. The optimized solar PV system became financially feasible only when net metering was introduced, allowing for excess energy sellback and significantly improving the cash flow and LCOE. Without net metering, the proposed system would require a grid price increase of approximately 482.76% above the current unsubsidized rate (US $ 0.029/kWh) to achieve viability. This underscores the urgent need for feed-in tariff policies and net metering mechanisms in TT to support RE adoption.

A standardized 100 kW solar PV system was also proposed as a scalable template for implementation across the nation's 134 public secondary schools. Although such a system may not generate excess energy for net metering, it still offers benefits such as reduced carbon emissions and a lower LCOE relative to unsubsidized grid electricity. However, in the absence of net metering, the overall cost-effectiveness remains limited.

In summary, the analysis highlights solar PV as the most technically and economically viable renewable option for secondary schools in TT, given its alignment with load profiles and cost structures. However, policy interventions—specifically, the introduction of net metering and feed-in tariffs—are essential to unlock the full potential of RE systems in the education sector and beyond.

5. Conclusion

This study demonstrated that solar PV systems are the most economically viable and practical RE option for secondary schools in TT. The project aimed to evaluate the school's hourly energy load profile and assess multiple RE configurations to optimize consumption. Through scenario-based simulations and detailed techno-economic analysis, solar PV has consistently emerged as the most favorable solution, particularly when supported by net metering policies.

The analysis revealed that RE integration becomes economically feasible at specific grid price thresholds: solar PV systems with batteries become viable at US$0.100/kWh, while wind energy becomes competitive only above US$0.120/kWh. However, standalone solar PV systems outperformed hybrid PV-wind models because of their higher renewable penetration, lower capital and operational costs, and better alignment with the school's daytime energy demand.

Battery storage was excluded from the optimized configurations because the grid remains a more cost-effective backup for intermittent renewable sources. Batteries may become attractive only in future scenarios with time-of-use rates or peak demand charges.

Crucially, net metering has been identified as a key enabler of economic viability. Without the ability to sell excess energy to the grid, the proposed system only becomes viable at a grid price approximately 482.76% higher than the current unsubsidized rate (US$0.029/kWh). With net metering, the proposed 473.3 kW solar PV system achieved a payback period of nine years, an IRR of 9.9%, and a LCOE of US$0.064/kWh. These results emphasize the urgent need for feed-in tariff policies and grid interconnection standards to facilitate RE deployment.

Additionally, a standardized 100 kW system was proposed for broader implementation across the country's 134 public secondary schools. Although such systems offer reduced carbon emissions and a lower LCOE, they are less cost-effective without net metering because of their inability to export excess energy.

This study provides critical insights for policymakers, educational institutions, and energy planners. This highlights the need to tailor RE solutions to specific load profiles and market conditions and underscores the role of policy in accelerating the adoption of clean energy technologies.

This study confirms the technical and economic feasibility of solar PV systems in educational institutions and reinforces the importance of net metering and supportive policies for expanding RE penetration. Future work should explore broader applications across different sectors and regions in TT and assess the implications of evolving energy markets and technological advancements.

6. Recommendations

Further analyses can be performed to refine the design and optimization of RE systems for secondary schools. The electricity consumption can be read hourly from the electrical meters to determine a more refined load profile, and an energy audit of the school can help identify areas to improve energy efficiency and future load requirements. A proposed budget for implementation could lead to restrictions in RE design and deliver a different approach and consideration for a solution. Further sensitivity analysis could be performed on the RE system costs and resources to correlate with future trends in component prices and understand how it could affect the design. While the study includes preliminary sensitivity analyses, particularly around electricity prices and grid feedback mechanisms, future research would benefit from a more comprehensive and systematic sensitivity analysis of critical input parameters. Variables such as solar radiation variability, future reductions in PV or battery costs, system lifespan, and potential fluctuations in net metering tariffs can significantly influence the economic viability and optimal system configuration. Incorporating probabilistic or scenario-based sensitivity analyses such as Monte Carlo simulations or tornado charts—can help capture the uncertainty in these inputs and provide more robust insights for decision-makers. This would improve the reliability of the model outcomes and better reflect real-world dynamics, particularly in markets subject to evolving energy pricing structures and technology costs. Design and optimization could also be achieved by prioritizing the lowest net emissions as the best solution. Further research can be conducted to expand the school loads in TT, where similar solutions can be scaled and implemented. Net metering enhances the economic benefits of RE systems, and further evaluation of feed-in tariffs and rates could provide valuable insights into establishing fair and favorable rates.

Acknowledgment

We would like to express special thanks to Ms. Amy Clark for assistance with the preparation of this research paper. We also gratefully acknowledge Hillview College for granting access to electricity consumption data and supporting the implementation of this study.

Conflict of Interest

The authors declare there are no conflict of interest.

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