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Hybrid Renewable Energy System Design and Economic-Environmental Analysis for Isolated Islands using HOMER Pro and Pareto-Fuzzy Optimization

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ABSTRACT

Remote islands in Malaysia currently rely heavily on diesel generators for electricity supply, resulting in high operational costs, significant carbon dioxide (CO_2) emissions, and fuel supply insecurity. Despite the abundance of solar and wind resources, improper system sizing and limited consideration of energy storage capacity frequently restrict renewable energy penetration in these regions. This study aims to develop a multi-objective sizing optimization framework to design a cost-effective and low-emission hybrid renewable energy system (HRES) comprising photovoltaic (PV) panels, wind turbines (WT), a diesel generator (DG), and a battery energy storage system (BESS). While HOMER Pro is a robust tool for generating sizing combinations, it is inherently limited to single-objective optimization based on cost minimization. To overcome this limitation, a Pareto–Fuzzy decision-making method was integrated into the analysis to perform multi-objective optimization considering both cost minimization and CO_2 emission reduction. The performance of these configurations was then compared against a conventional diesel-only baseline to evaluate their overall effectiveness. Results demonstrate that the Pareto-Fuzzy optimized HRES achieves a 49% reduction in CO_2 emissions and increases the renewable fraction to 91.8% compared to the HOMER cost-optimal configuration, while incurring only marginal increases of 1.45% in Net Present Cost (NPC) and 1.44% in Levelized Cost of Energy (LCOE), highlighting an effective trade-off between economic and environmental performance. Critically, the Pareto-Fuzzy solution outperforms the diesel-only baseline in terms of cost-effectiveness while delivering significantly lower annual CO_2 emissions. Consequently, this research confirms that the integration of Pareto-Fuzzy multi-objective optimization provides a superior and more sustainable pathway for isolated HRES by achieving substantial environmental gains with negligible economic impact.

1. Introduction

Access to reliable, affordable, and sustainable electricity remains a critical challenge for many isolated and remote communities in Malaysia. These regions, particularly island-based populations such as those on Tioman Island, often rely on diesel generators to meet their electricity needs [1], [2], [3]. This approach results in significant drawbacks, including high operational costs, dependence on fluctuating fossil fuel markets, and substantial carbon emissions. With growing awareness of climate change and the need for sustainable development, there is increasing global and national momentum to decarbonize the power sector [4], [5].

Renewable energy sources (RESs) such as solar and wind offer a viable alternative, especially in locations with abundant natural resources [6], [7]. Hybrid renewable energy systems (HRES) combining solar photovoltaic (PV), wind turbines (WT), and battery energy storage systems (BESS) provide a promising solution for islanded microgrids [8]. These systems improve energy autonomy and reduce environmental impacts, yet the performance and economic feasibility of such systems depend greatly on optimal sizing and configuration. A poorly sized system may result in energy shortfalls or economic inefficiency, undermining the benefits of renewable integration.

Most existing island microgrid designs prioritize cost minimization, typically relying on diesel generators or limited renewable energy integration. In many cases, energy storage systems (ESSs) are either under-sized or excluded due to conservative cost assumptions and restricted search ranges during optimization [9]. As a result, renewable energy penetration remains sub-optimal and carbon emission reduction potential is not fully exploited. Furthermore, single-objective optimization approaches are insufficient to address the inherent trade-offs between economic performance and environmental sustainability. Therefore, a comprehensive multi-objective optimization framework that incorporates realistic battery modeling and systematic decision-making is required. To establish the technical foundation for this framework, the subsequent section reviews current methodologies in microgrid optimization and identifies the specific gaps in existing multi-objective algorithms.

2. Related Works

This section reviews the fundamental principles of multi-objective sizing, evaluates the technical tools currently utilized in HRESs planning, and provides a comparative analysis of recent scholarly contributions to the field.

2.1. Sizing Optimization Formulation

In the design of HRES, multi-objective sizing optimization is a key process used to determine the optimal capacity of components like PV, wind turbines, and diesel generators to ensure economic and sustainable operation. This procedure balances primary objectives such as economics, environmental impact, and power supply reliability by navigating trade-offs based on local resource availability and technical constraints [3].

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2.1.1. Economic Objective

The most used economic assessment metric is the levelized cost of electricity (LCOE) [7], which measures the average cost per kWh of electricity over the entire life cycle of the system, covering investment, operation, maintenance, and fuel costs. In addition, Net Present Cost (NPC) is often used to assess overall system expenditures [9].

2.1.2. Environmental Objective

Minimizing dependence on diesel generation directly translates to lower carbon emissions, aligning with environmental sustainability goals and supporting Malaysia's national green energy initiatives [10].

2.1.3. Technical Objective

In order to ensure a continuous power supply from an off-grid microgrid, attention must be paid to the system's ability to reliably meet demand. Commonly used reliability metrics include the Loss of Load Probability (LOLP) or the Loss of Load Supply Probability (LPSP) and Loss of Load Hours (LOLH). These metrics quantify the probability or the expected duration that the system fails to satisfy the load requirement, providing a critical measure for system design and adequacy assessment [4]. By weighing these three types of objectives, the optimization model can identify the system configuration that has the lowest cost and emissions while ensuring a stable power supply, a strategy particularly important for remote areas [11].

2.2. Sizing Optimization Technique

Developed by the National Renewable Energy Laboratory (NREL), Hybrid Optimization of Multiple Energy Resources (HOMER) is specialized software for modeling, optimizing, and analyzing HRESs and microgrids. Its main function is to help users design economical, reliable, and environmentally friendly energy systems through detailed system modeling, optimization analysis, and sensitivity testing [12].

The HOMER software can consider multiple energy resources simultaneously, such as solar, wind, diesel generation, BESS, and grid connections, and is suitable for modeling off-grid, grid-connected, and micro-grid energy systems. In recent years, HOMER Pro has become one of the most widely used software platforms in microgrid research and engineering practice and is widely used for energy planning in off-grid communities, islanded systems, and remote industrial facilities [3].

2.3. Comparative Analysis of Sizing Optimization in Renewable Energy Systems

The optimization of HRES has become a focal point of contemporary research with various methodologies employed to balance technical reliability, economic viability, and environmental impact. A comprehensive review of the recent literature from 2019 to 2025 as summarized in Table 1 reveals that the predominant approach in the field relies heavily on the use of HOMER software as a standalone simulation tool across diverse geographical landscapes. This software has been widely utilized due to its robust database and ability to perform complex techno-economic assessments for both grid-connected and off-grid configurations in areas such as Morocco’s Eastern Sahara in Reference [13] and Tilos Island in Greece in Reference [14]. For instance, Reference [15] and Reference [3] utilized HOMER to evaluate the feasibility of wind and solar integration in coastal regions such as Baluchistan’s Seashore and the South China Sea while focusing primarily on minimizing the NPC. This trend of utilizing HOMER’s internal optimization continued through more recent studies such as Reference [16] which focused on school electrification in Malawi and Reference [17] which addressed the energy needs of a hospital in Malaysia. Even in the most current research from 2025 such as the works of Reference [18] in Turkey, Reference [19] in Bangladesh, and Reference [20] in India, HOMER remains the primary engine for sizing components like PV, wind turbines, and BESS.

However, a critical gap exists in these studies because while HOMER is excellent at generating a list of feasible system configurations, its internal ranking is often biased toward a single objective which is typically cost. This creates a limitation when researchers aim to achieve a precise trade-off between conflicting goals such as cost minimization and CO2 emission reduction as the software lacks a native mechanism to mathematically weigh these competing priorities without subjective intervention. To address the limitations of standalone simulation software, some researchers have moved toward alternative mathematical models or multi-criteria decision-making tools in unique settings. Reference [21] employed Mixed-Integer Linear Programming (MINLP) for integrated CSP-CHP systems while Reference [22] explored metaheuristic algorithms to navigate the complex search space of HRES in Southeast Asia. Furthermore, Reference [23] introduced the TOPSIS method to rank potential configurations for a district in India and provided a more structured decision-making process than basic simulation. Nevertheless, these methods often require significant computational effort or depend on subjective weighting factors that can lead to inconsistent results when applied to sensitive ecological zones.

In contrast, the proposed approach for Tioman Island, Malaysia, addresses these shortcomings by uniquely integrating HOMER with the Pareto-Fuzzy method. This hybrid framework extracts the non-dominated solutions from HOMER to form a Pareto front and then applies fuzzy membership functions to select the best-compromise solution. This study provides a mathematically rigorous framework that eliminates subjectivity by ensuring that both economic costs and carbon footprints are minimized to their most optimal equilibrium. Such an integration represents a significant methodological advancement over the traditional HOMER-only approaches identified in the current literature and offers a more balanced decision-making tool for sustainable energy planning in islanded environments.

2.4. Contributions

This study aims to develop an optimized multi-objective sizing strategy for HRESs tailored to isolated island in Malaysia, specifically focusing on the case of Tioman Island. The contributions of this study are as follows:

i. To optimize the sizing of a HRES including PV, wind turbine, diesel generator, and BESS using HOMER Pro software considering cost minimization.
ii. To design an optimal multi-objective sizing framework for HRES using the Pareto-Fuzzy method considering cost minimization and carbon emission reduction.
iii. To evaluate the performance of HOMER Pro and Pareto-Fuzzy optimized systems against a conventional diesel generator baseline in terms of cost-effectiveness and emissions reduction.

The remainder of this paper is organized as follows. Section 3 provides the detailed system description and Section 4 defines the optimization formulations. The optimization technique utilized in this study is elaborated in Section 5, followed by the presentation and analysis of the results and discussions in Section 6. Finally, the research findings are summarized in the conclusion in Section 7.

3. System Description

The HRES architecture is illustrated in Figure 1. This configuration utilizes a dual-bus topology where the AC bus supports diesel generator units (Cmns100) and the primary electric load, while the DC bus integrates wind turbines (WES250), solar PV arrays, and a 100Li-ion BESS. A bidirectional converter manages the power exchange between the buses to ensure stability and maximize renewable penetration.

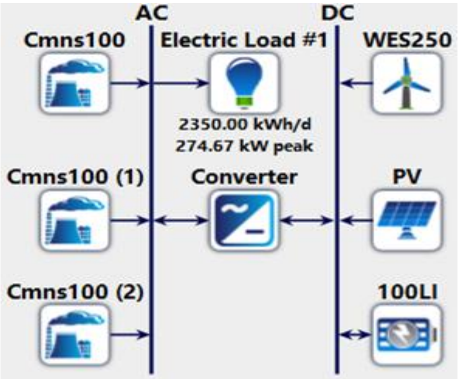

Figure 1. HRES configuration integrating PV, wind turbine (WES250), BESS, and diesel generators (Cmns100)

Table 1. Comparison of the proposed approach with other related studies available in the field of HRES sizing optimization

Year	Area Selection	Mode		Objective function		Optimization Method	Sizing	Generation						BESS	Ref
		Grid	Off- grid	Cost	CO2 Emission			Generator	WT/TT	PV	FC	EV	Grid		
2019	Eastern Sahara, Morocco		√	√	√	HOMER	√	√	√	√				√	[13]
2020	Hybrid CSP-CHP		√	√	√	MINLP	√		√	√				√	[21]
2021	South China Sea, Malaysia	√		√	√	HOMER	√		√	√			√	√	[3]
2021	Tilos Island, Greece		√	√	√	HOMER	√		√	√				√	[14]
2021	Seashore, Baluchistan	√		√	√	HOMER	√		√	√			√		[15]
2021	Sidhwanbet, India.	√	√	√	√	TOPSIS	√	√	√	√	√		√	√	[23]
2022	Far North Region, Cameroon		√	√		HOMER	√			√	√			√	[24]
2023	Blantyre Secondary School, Blantyre, Malawi	√		√	√	HOMER	√	√	√	√				√	[16]
2023	Residential Building		√	√		HOMER	√	√		√				√	[25]
2023	Jafrabad, India		√	√	√	HOMER	√	√	√	√				√	[26]
2024	Hospital, Malaysia		√	√	√	HOMER	√	√	√	√				√	[17]
2024	Southeast Asia		√	√	√	Metaheuristic	√	√	√	√				√	[27]
2024	Laghouat	√		√	√	HOMER	√		√	√			√	√	[28]
2024	Nsukka, Enugu State, Nigeria		√	√		HOMER	√	√	√	√				√	[29]
2025	Hatay, Turkey	√	√	√	√	HOMER	√	√		√	√		√		[18]
2025	Hatiya Upazila, Bangladesh	√		√	√	HOMER	√		√	√			√	√	[19]
2025	'Kanur,' Maharashtra, India		√	√	√	HOMER	√	√	√	√				√	[20]
2025	Tioman Island, Malaysia		√	√	√	HOMER Pro and Pareto-Fuzzy	√	√	√	√				√	Proposed approach

3.1. Site Selection

The study is centered on Tioman Island, Malaysia, a remote location characterized by a high dependency on diesel generation and significant potential for renewable resource integration. This site was selected due to its representative load profile for isolated resort-based island communities. The geographical coordination of the selected site is presented in Figure 2.

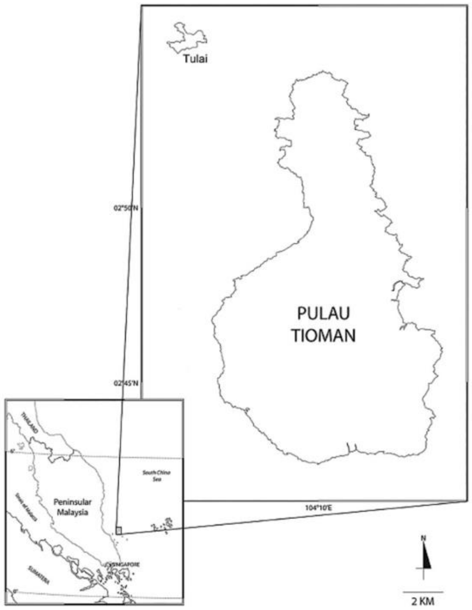

Figure 2. Geographical coordinates of the case study

3.2. Load Profile

The electrical load profile was constructed based on the Tioman Island resort case study and further adjusted to reflect seasonal and hourly demand variations. The total average daily electricity demand is estimated at 9,126.49 kWh/day. Figure 3 illustrates the hourly load demand distribution used for the system simulation.

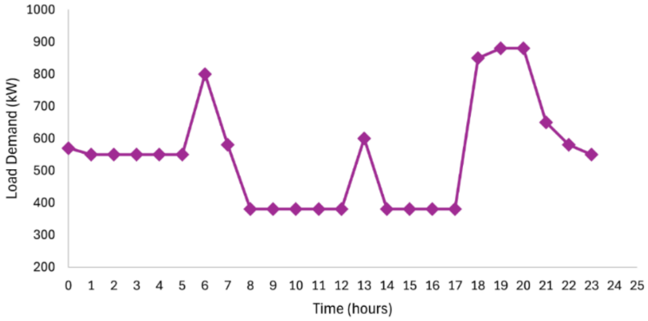

Figure 3. Hourly load demand profile of the Tioman Island resort

3.3. Solar Power System

Renewable resource inputs for the solar power system were sourced from NASA Power. The analysis utilizes an annual solar irradiance averaging 5.133 kWh/m²/day, which serves as the primary input for determining the PV capacity. The average monthly solar radiation data for the site is depicted in Figure 4.

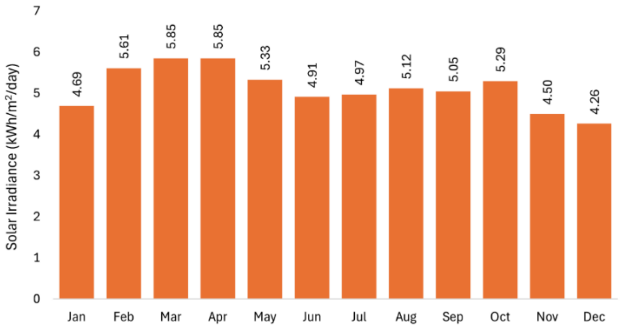

Figure 4. Average monthly solar radiation data

3.4. Wind Power System

Wind resource data was also obtained from NASA Power to assess the feasibility of the wind power system. The site exhibits an average wind speed of 4.3 m/s, which is a critical metric for evaluating the contribution of wind energy to the overall hybrid generation mix. The average monthly wind speed data is detailed in Figure 5.

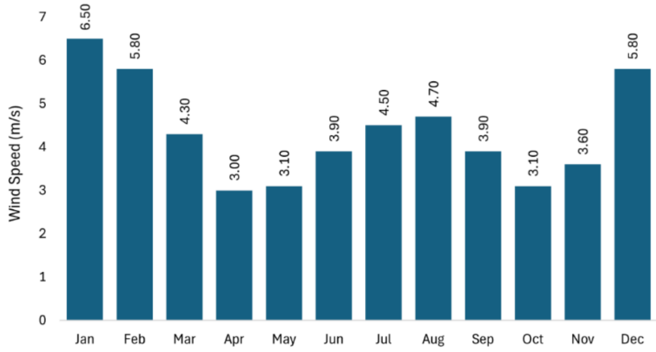

Figure 5. Average monthly wind speed data

3.5. Ambient Temperature

The temperature data completes the environmental dataset necessary for accurate system simulation. Figure 6 displays the average monthly temperature data for the selected region.

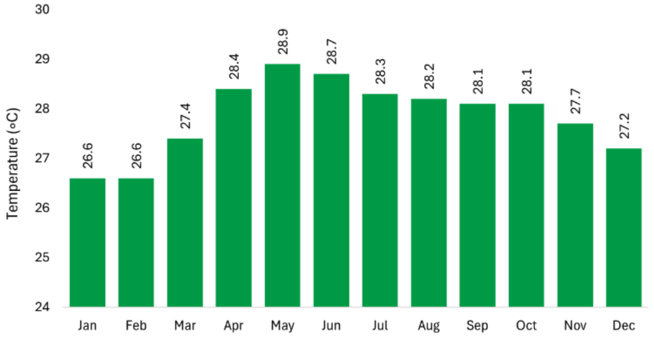

Figure 6. Average monthly temperature data

3.6. Battery Energy Storage System

The suggested design incorporates the 100Li-ion battery model within the hybrid energy system. This configuration utilizes Lithium-ion technology with a capital cost (CC) of $450 per unit, a replacement cost (RC) of $300 per unit, and an annual operation and maintenance cost (O&MC) of $500 per unit. The optimization framework considers a deployment range between 10 and 300 units to meet the storage requirements of the HRES.

3.7. System Converter

The proposed design utilizes a system converter integrated into the HOMER Pro software, which operates in both inverter and rectifier modes to manage power flow between the AC and DC buses. The configuration is based on a capital cost of $890 per kW and a replacement cost of $800 per kW, with an annual operation and maintenance cost of $10 per kW. For the optimization process, the converter capacity is defined within a size range of 100 kW to 1000 kW. The input parameters for the HRES components, as summarized in Table 2, form the basis for the optimization model.

4. Optimization Formulations

4.1. Net Present Cost (NPC)

The NPC represents the total present value of all costs incurred over the system's lifetime, including initial capital, component replacement, and operation and maintenance [28]. The NPC is calculated as follows in Equation (1).

$$TNPC = CC + RC + O\&MC \qquad (1)$$

Where $TNPC$ is the total net present cost ($), CC is the initial capital cost ($), RC is the replacement cost ($) and $O\&MC$ is the total operation and maintenance cost ($).

4.2. Levelized Cost of Energy (LCOE)

The LC OE is an economic metric used to assess the average cost per unit of useful electrical energy produced by the system throughout its operational life [29]. It is defined in Equation (2).

$$LCOE = \frac{TNPC}{\sum_{t=1}^{8760} E_{gen}(t)} \qquad (2)$$

where $LCOE$ is the levelized cost of energy ($/kWh), $E_{gen}(t)$ is the total electricity generated by the system at hour t (kWh).

4.3. CO2 Emission

CO2 emissions are calculated based on total annual fuel consumption by assuming nearly all carbon in the fuel is converted to CO2 during combustion at a ratio of 3.67g per gram of carbon, as shown in Equation (3).

$$CO_2\ Emissions = (Fuel\ consumed) \times (Carbon\ content) \times 3.67 \qquad (3)$$

Table 2. The data for system components in HRES

System parameters	Value	Units
(a) PV		
Capital Cost	2,000	$/kW
Replacement Cost	2,000	$/kW
O&M Cost	10	$/kW/year
Size range	100 – 1000	kW
(b) WT		
Model	WES250	
Capital Cost	37,500	$/unit
Replacement Cost	262,500	$/unit
O&M Cost	7,500	$/unit/year
Size range	1 – 10	units
(c) BESS		
Model	100Li-ion	
Capital Cost	450	$/unit
Replacement Cost	300	$/unit
O&M Cost	500	$/unit/year
Size range	10 – 300	units
(d) Diesel Generator		
Model	Cmns100	
Capital Cost	220	$/kW
Replacement Cost	200	$/kW
O&M Cost	0.3	$/h
Size range	1 – 3	units
(e) Converter		
Capital Cost	890	$/kW
Replacement Cost	800	$/kW
O&M Cost	10	$/kW/year
Size range	100 – 1000	kW

5. Optimization Technique

5.1. HOMER Pro Software

This study utilizes HOMER Pro, a platform developed by the National Renewable Energy Laboratory (NREL), to optimize and conduct sensitivity analyses for HRES. The software evaluates both grid-connected and off-grid configurations by simulating various component sizes and combinations against specific load requirements and local resource data. This process identifies the most viable system designs by prioritizing cost as the metrics, specifically the NPC and LCOE.

5.2. Pareto-Fuzzy Optimization

This study adopts a multi-objective optimization approach to include environmental sustainability and energy affordability. This methodology integrates Pareto analysis and fuzzy logic decision-making to select the most suitable system configuration. These techniques allow for a balanced evaluation of conflicting goals beyond a single economic objective, ensuring the final design aligns with both financial and sustainability targets.

All feasible solutions generated in HOMER Pro are evaluated in the Pareto-Fuzzy multi-objective approach, which selects the optimal configuration from the set of non-dominated solutions based on the objective functions. A solution is classified as dominated if another candidate performs equally or better across all objectives while being strictly superior in at least one; conversely, non-dominated solutions form the Pareto frontier. To resolve trade-offs between minimizing NPC, LCOE, and CO2 emissions, a fuzzy membership value, μ_{fit}, ranging from 0 (worst) to 1 (best), is assigned to each objective using the following minimization formula [30]:

$$\mu_{fit_i}^{obj} = \begin{cases} 1 & fit_i^{obj} \le fit_{min}^{obj} \\ \dfrac{fit_{max}^{obj} - fit_i^{obj}}{fit_{max}^{obj} - fit_{min}^{obj}} & fit_{min}^{obj} < fit_i^{obj} < fit_{max}^{obj} \\ 0 & fit_i^{obj} \ge fit_{max}^{obj} \end{cases} \qquad (4)$$

Once individual memberships are determined, they are aggregated into a global membership value, μ_i, for each solution i across N_{obj} objectives and M non-dominated solutions:

$$\mu_i = \frac{\sum_{Obj=1}^{N_{obj}} \mu_{fit_i}^{obj}}{\sum_{i=1}^{M} \sum_{Obj=1}^{N_{obj}} \mu_{fit_i}^{obj}} \qquad (5)$$

The best compromise solution is identified as the configuration achieving the highest aggregate membership value, mathematically defined as:

$$max\{\mu_i\} \qquad (6)$$

This framework ensures the final system selection achieves a mathematically balanced performance between economic feasibility and environmental sustainability. The overall process of the proposed approach is shown in Figure 7.

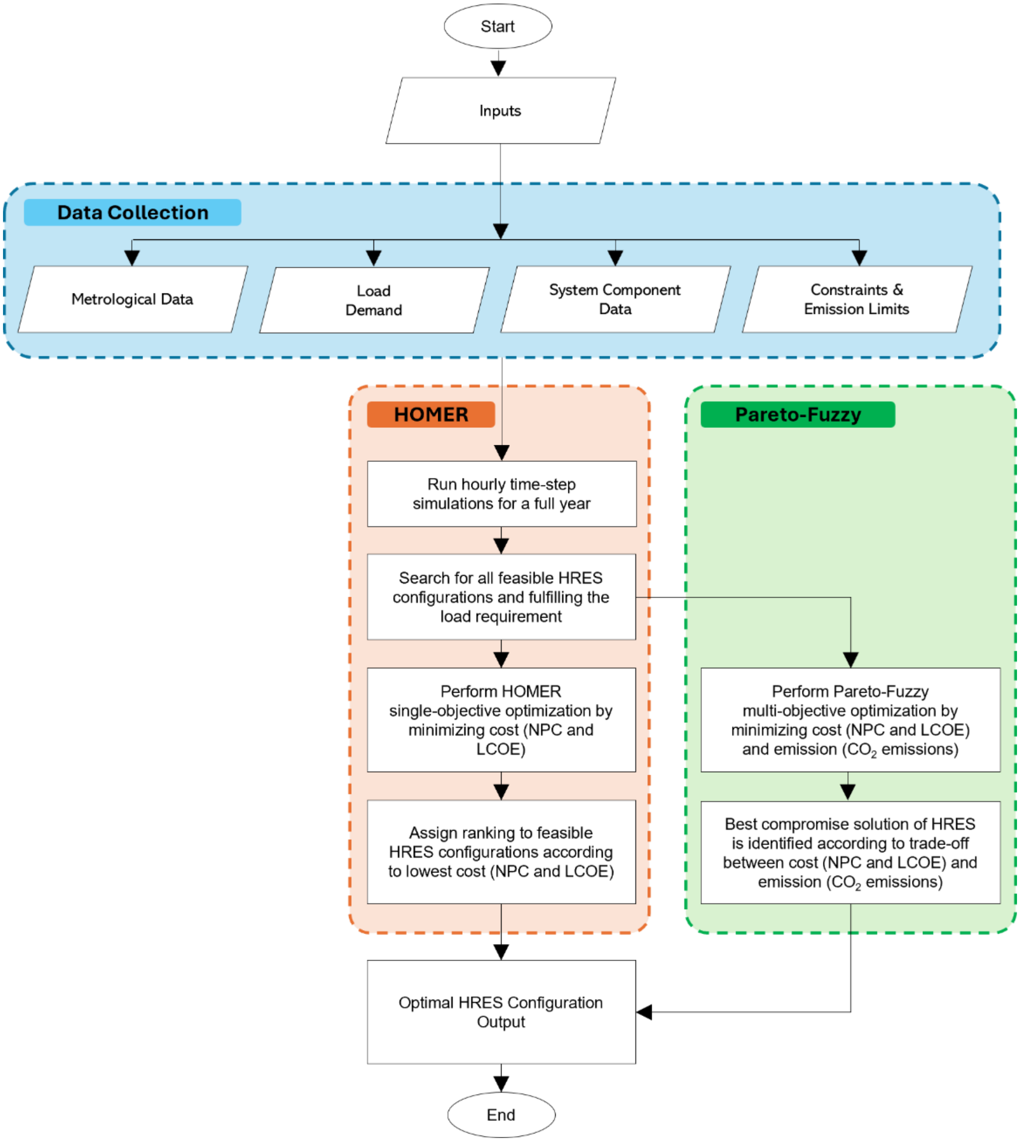

Figure 7. Flowchart of the proposed HOMER Pro and Pareto-Fuzzy optimization approach

6. Results and Discussions

This section evaluates the performance of the proposed HRES for Tioman Island by comparing two distinct optimization strategies to determine the most viable configuration. The analysis investigates the technical and economic trade-offs between a cost-centric approach and an integrated environmental-economic framework, categorized as follows:

Approach 1: HOMER Pro Optimal Solution, a single-objective optimization for cost minimization only.

Approach 2: Pareto-Fuzzy Optimal Solution, a multi-objective optimization designed to balance cost minimization with CO2 emissions minimization.

6.1. HOMER Pro Optimal Solution

The initial phase of the study involved a comprehensive simulation using HOMER Pro, which generated approximately 2,000 feasible HRES configurations for the Tioman Island. To provide a clear overview of the system's economic trends, Table 3 presents the top 20 configurations ranked by the lowest NPC and LCOE. This ranking illustrates how variations in PV capacity, wind turbine units, and BESS directly influence the initial capital investment and long-term operating costs.

Table 3. Top 20 HRES configurations

PV (kW)	WT (unit)	Diesel Gen (unit)	BESS (unit)	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)	CAPEX ($)	Ren Frac (%)	Total Fuel (L/yr)	CO_2 (kg/yr)
400	2	2	30	2149185	0.193842	83716.38	1066940	88.89793	37456.36	98929.86
400	2	2	28	2149286	0.193851	83793.79	1066040	88.56987	38550.18	101818.9
400	2	2	27	2149530	0.193874	83847.5	1065590	88.3947	39112.19	103303.2
400	2	2	31	2149914	0.193908	83737.98	1067390	89.04156	36969.67	97644.42
400	2	2	25	2152951	0.194182	84181.75	1064690	87.99301	40462.29	106869.1
400	2	2	33	2153039	0.19419	83910.11	1068290	89.29665	36124.87	95413.13
400	2	2	34	2155390	0.194402	84057.09	1068740	89.40231	35763.33	94458.22
300	3	2	27	2160137	0.194837	97238.11	903090	87.16463	43169.49	114019.4
300	3	2	28	2160387	0.194859	97222.59	903540	87.32137	42645.76	112636.1
300	3	2	26	2160433	0.194863	97295.78	902640	86.99267	43735.31	115513.9
300	3	2	25	2162230	0.195025	97469.64	902190	86.79146	44416.98	117314.3
300	3	2	31	2162987	0.195094	97319.32	904890	87.75104	41217.38	108863.5
400	3	2	28	2164665	0.195235	82082.64	1103540	92.23347	26536.93	70089.41
400	3	2	27	2165707	0.195329	82198.03	1103090	92.04701	27160.39	71736.13
400	3	2	30	2165869	0.195344	82106.16	1104440	92.54355	25543.55	67465.71
400	3	2	31	2166862	0.195427	82148.18	1104890	92.67886	25077.26	66234.15
400	2	2	38	2167082	0.195457	84822.32	1070540	89.78711	34493.79	91105.11
500	2	2	30	2169796	0.195696	69839.84	1266940	93.40428	22608.72	59714.24
500	2	2	31	2170313	0.195743	69845.05	1267390	93.55235	22105.68	58385.59
500	2	2	28	2170548	0.195764	69967.66	1266040	93.05994	23752.91	62736.28

From this extensive list of feasible solutions, the single most cost-effective configuration was identified as the optimal solution for Approach 1. The specific technical and economic parameters for this optimal selection are detailed in Table 4.

Table 4. Objective function value and optimal size of HRES in Approach 1

	Parameter	Value
Objective function	NPC ($)	2,149,185.00
	LCOE ($)	0.1938/kWh
	CO_2 Emission (kg/year)	98,929.86
Optimal size	PV size (kW)	400
	WT (unit)	2
	BESS (unit)	30
	Diesel Generator (unit)	2
Performance	Renewable Fraction (%)	88.90

The results from Table 4 demonstrate that the optimal configuration for Approach 1 comprises 400 kW of PV, 2 units of WT, 30 units of BESS, and 2 units of diesel generators. This setup achieves an NPC of $2,149,185.00 and a LCOE of $0.1938/kWh. From a technical perspective, the system operates with a high renewable fraction of 88.90%, significantly reducing the dependency on fossil fuels.

However, the analysis of these results reveals a critical trade-off because Approach 1 focuses exclusively on cost minimization, the resulting CO2 emissions remain relatively high at 98,929.86 kg/year. While the configuration is financially optimized, the reliance on diesel generators to cover the remaining 11.1% of the load contributes to a substantial carbon footprint. This highlights the limitation of single-objective optimization, as the least-cost system often conflicts with Tioman Island's environmental targets.

6.2. Pareto-Fuzzy Optimal Solution

A multi-objective framework balances cost against CO2 emissions, identifying the optimal trade-off via a Pareto frontier. By applying a fuzzy membership function, the most balanced HRES configuration for the Tioman Island is selected from this set. The 3D visualization in Figure 8 highlights the trade-off between costs and emissions, leading to the optimal HRES capacities and performance metrics presented in Table 5 for Approach 2.

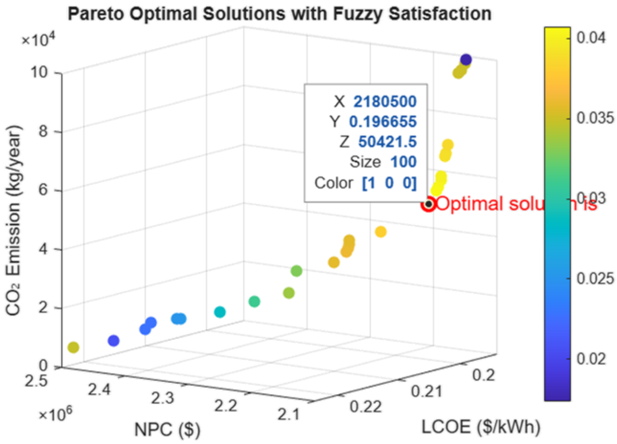

Figure 8. Pareto-optimal solutions for the HRES configuration

Table 5. Objective function value and optimal size of HRES in Approach 2

	Parameter	Value
Objective function	NPC ($)	2,180,500.00
	LCOE ($)	0.1966/kWh
	CO_2 Emission (kg/year)	50,421.00
Optimal size	PV size (kW)	500
	WT (unit)	2
	BESS (unit)	38
	Diesel Generator (unit)	2
Renewable Fraction (%)		91.80

Based on this selection process, Approach 2 consists of a system architecture with 500 kW PV, 2 units of WT, 2 units of diesel generators, and 38 BESS units. As shown in Table 5, this configuration results in an NPC of $2,180,500.00 and an LCOE of $0.1966/kWh. Despite the slight increase in cost, the annual CO2 emissions drop significantly to 50,421.00 kg/year, while the renewable fraction increases to 91.80%. These results demonstrate that the multi-objective approach effectively minimizes diesel generator reliance and provides a more sustainable energy solution by balancing economic viability with environmental responsibility.

6.3. Comparative Analysis of Approach 2 HRES and Diesel-only Systems

A comparative analysis was performed to evaluate the performance of the optimal HRES configuration from Approach 2 against a conventional diesel-only system. This comparison highlights the economic and environmental advantages of transitioning toward a hybrid renewable framework for Tioman Island.

As shown in Figure 9 and 10, the optimal HRES provides a significant reduction in total project costs. The NPC is reduced by approximately 46.7%, dropping from $4,093,978.00 in the diesel-only scenario to $2,180,500.00. This economic efficiency is further reflected in the LCOE, which decreases from $0.3692/kWh to $0.1966/kWh. These findings indicate that the integration of PV, WT, and BESS significantly lowers the long-term financial burden compared to a system reliant solely on fossil fuel combustion.

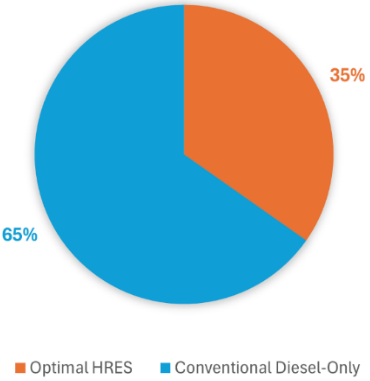

Figure 9. NPC comparison between the diesel-only baseline and Pareto-Fuzzy optimized HRES

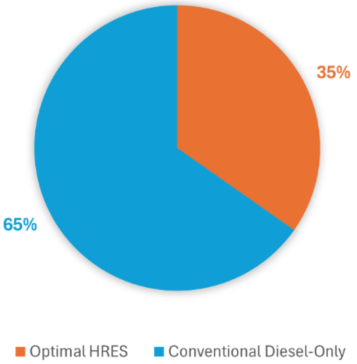

Figure 10. LCOE comparison between the diesel-only baseline and Pareto-Fuzzy optimized HRES

Furthermore, the environmental impact as illustrated in Figure 11 shows a drastic reduction in annual CO2 emissions, which fall from 834,813.00 kg to 50,421.00 kg. This represents a 94% decrease in the carbon footprint. These results confirm that the Pareto-Fuzzy optimal solution not only offers a more affordable energy source but also aligns with sustainability goals by nearly eliminating the carbon output associated with traditional diesel power generation on the island.

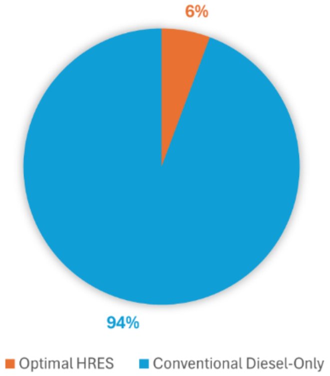

Figure 11. CO_2 emission comparison between the diesel-only baseline and Pareto-Fuzzy optimized HRES

7. Conclusion

This study successfully developed a multi-objective sizing optimization framework for a HRES on Tioman Island, addressing the limitations of conventional diesel-reliant power systems by integrating Pareto-Fuzzy decision-making with HOMER Pro simulations. The findings reveal that while Approach 1 establishes the minimum financial baseline, Approach 2 achieves a superior balance by reducing CO_2 emissions by 49% and increasing the renewable fraction to 91.8%, with only marginal increases of 1.45% in Net Present Cost (NPC) and 1.44% in Levelized Cost of Energy (LCOE). Furthermore, compared to the conventional diesel-only baseline, the optimized HRES demonstrates enhanced cost-effectiveness while significantly reducing the annual carbon footprint. These results confirm that a multi-objective strategy is more effective for HRES in isolated island planning, proving that substantial environmental gains can be realized with negligible economic impact, ultimately providing a robust pathway toward energy security and decarbonization for remote regions.

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