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Hybrid vs. Standalone: The Complexity of Energy System Choices

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Abstract—Our study, using HOMER simulations, highlights the complexity of choosing between standalone photovoltaic and hybrid systems. The research demonstrates that the optimal choice depends on multiple factors, necessitating case-by-case analysis. Simulations were conducted at two different sites with varied load profiles, revealing that local conditions, costs, and energy demands significantly influence system suitability. This research emphasizes the importance of comprehensive analysis in energy system planning, as the superiority of hybrid systems over standalone solutions varies across different contexts.

Keywords—HOMER simulations; standalone systems; hybrid systems; load profiles; site-specific conditions.

I. INTRODUCTION

Energy is a fundamental pillar for economic and social development worldwide. As global energy demand continues to rise and environmental concerns become increasingly pressing, the search for sustainable and efficient energy solutions is paramount. Among the available options, photovoltaic (PV) systems and generators are two of the most commonly used technologies to provide electricity, particularly in off-grid or poorly electrified areas ([9]; [18]).

The transition to renewable energy, driven by environmental concerns and the need to reduce our dependence on fossil fuels, has placed renewable energies, particularly photovoltaics, at the forefront of global concerns. As a mature and continuously evolving technology, photovoltaics offer a promising solution to meet the growing demand for clean and decentralized power ([3]; [14]). However, the intermittency of solar production, due to variations in sunlight, requires complementary solutions to ensure continuous and reliable electrical power supply ([5]; [15]).

While both PV systems and generators offer distinct advantages, they also have their limitations. PV systems are environmentally friendly and can be a source of renewable energy, but their performance is heavily dependent on weather conditions ([10]; [13]). On the other hand, generators offer greater flexibility and reliability but are often costly to operate and have a significant environmental impact ([12]; [17]). Hybrid systems, which combine PV panels and generators, have emerged as a potentially more efficient solution. These systems aim to leverage the strengths of each technology while mitigating their weaknesses ([4]; [9]). However, a critical question remains: Are hybrid systems truly more advantageous than standalone PV systems or generators?

Madagascar, an island nation blessed with abundant solar resources, presents a fascinating case study in the adoption of renewable energy technologies. The country's tropical climate and vast solar potential have sparked debates about the most effective approach to harnessing these natural resources for power generation. A prevailing assumption suggests that in such solar-rich environments, large-scale standalone photovoltaic (PV) systems or conventional generators (GE) should be the preferred choice

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over hybrid systems that combine both technologies (PV + GE). However, this preconception warrants closer examination, particularly in light of the unique challenges and opportunities presented by Madagascar's diverse geographical and socio-economic landscape.

Hybrid photovoltaic-diesel generator systems have emerged as a compelling alternative, especially in off-grid areas or applications demanding uninterrupted power supply. These systems ingeniously combine the strengths of photovoltaics (zero-fuel costs, environmental friendliness) with those of diesel generators (reliability, on-demand power), offering enhanced autonomy and dependability ([1]; [6]; [12]). The synergy between these technologies promises a more resilient and adaptable energy solution, potentially addressing the multifaceted energy needs of a developing nation like Madagascar.

Our study aims to challenge prevailing assumptions by conducting a rigorous comparison of standalone and hybrid systems within the Malagasy context. Utilizing HOMER (Hybrid Optimization of Multiple Energy Resources) software, we have simulated various system configurations at two distinct locations with diverse load profiles. This approach allows us to evaluate the performance, cost-effectiveness, and reliability of different energy solutions under real-world conditions. Our analysis focuses on three primary system types - hybrid, standalone PV, and standalone generator - taking into account critical factors such as:

- Site-specific characteristics: solar irradiation, temperature variations, wind patterns, etc. ([4]; [7]; [8]; [10]; [11]; [13]; [17])
- Electrical consumption patterns : load profiles, peak power demands, etc. ([7] ; [8] ; [11] ; [16] ; [17])
- Equipment costs: solar panels, energy storage systems, diesel generators, inverters, etc. ([2]; [7])
- Energy pricing: grid electricity rates, fuel costs, etc. ([7]; [16])
- Financial incentives: government subsidies, tax exemptions, etc. ([7]; [16]; [19])

The optimal system configuration for each scenario is determined based on two key economic indicators: the Net Present Cost (NPC) and the cost of energy (COE). These metrics provide a comprehensive view of the long-term financial viability of each energy solution.

Through these simulations, we address a fundamental question: In a tropical country with high solar potential like Madagascar, are hybrid systems a necessity for optimal energy provision, or simply one option among many viable alternatives? Our study aims to provide clear, objective insights to guide decision-making in selecting the most appropriate energy solutions for Madagascar's diverse contexts.

The findings of this research will contribute to a deeper understanding of the advantages and limitations of both hybrid and standalone systems in tropical climates. By exploring the nuanced interplay between technological, economic, and environmental factors, we offer valuable guidance to policymakers, energy planners, and industry stakeholders. Our work illuminates the complex landscape of renewable energy adoption in Madagascar, with implications that extend to other regions facing similar challenges in their transition to sustainable energy systems ([7]; [16]).

As the global community grapples with the urgent need for sustainable energy solutions, our study provides a data-driven framework for evaluating the efficacy of different approaches. By challenging preconceptions and offering a nuanced analysis of energy system choices, we aim to contribute to the development of more resilient, cost-effective, and environmentally friendly power generation strategies in Madagascar and beyond.

II. PRESENTATION OF ENERGY SYSTEMS

A. Standalone Photovoltaic System

Photovoltaic systems convert sunlight into electricity using solar cells, based on the photovoltaic effect. They harness an inexhaustible, free energy source and produce no emissions, contributing to environmental preservation. Installation is relatively simple. However, electricity production varies with weather conditions, and the initial investment can be significant.

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B. Standalone Generator

Generators produce electricity from mechanical energy via a heat engine driving an alternator. They offer flexibility, quick start-up, adjustable power, and immediate electricity availability. Disadvantages include high operating costs due to fuel consumption, greenhouse gas emissions, air pollution, and noise.

C. Hybrid Photovoltaic-Generator System

Hybrid systems combine photovoltaics and generators, offering a more complete and reliable energy solution. Components include solar panels, batteries, an inverter, and a generator. Advantages include complementary energy sources, improved reliability, and great autonomy, especially in isolated areas. However, these systems are more complex to design and manage, requiring advanced technical expertise. The initial investment is generally higher than standalone systems due to additional components.

III. MATERIALS AND METHODS

A. HOMER Software Overview

HOMER is a powerful tool designed to model and optimize hybrid energy systems in detail. It simulates the operation of complex systems integrating various energy sources (solar, wind, diesel, etc.) and storage options (batteries), accounting for the interactions between these components.

With HOMER, it is possible to evaluate energy systems based on multiple criteria, such as capital and operating costs, greenhouse gas emissions, and energy efficiency. The software then identifies the optimal system configuration, i.e., the one that best meets the defined objectives (minimizing costs, maximizing renewable energy production, etc.) while considering technical.

Moreover, HOMER incorporates detailed climatic data, enabling accurate simulation of the performance of solar and wind systems throughout the seasons. Finally, its user-friendly interface facilitates model creation and result visualization, making the tool accessible to a wide range of users.

B. Evaluation of Energy Systems with HOMER

HOMER provides a comprehensive assessment of energy systems, focusing on several key criteria:

- Performance: The software analyzes the efficiency of each component and optimizes energy production to meet specific needs in the most effective manner.
- Technical feasibility: HOMER simulates and evaluates the system design, ensuring a harmonious integration of technologies.
- Economic viability: It calculates investment and operating costs. It computes the COE, return on investment (ROI), and payback period, allowing for comparisons of the profitability of different energy configurations.
- Environmental impact: HOMER assesses the system's carbon footprint, analyzes resource utilization, and helps identify configurations that minimize environmental impacts while meeting energy demands.

By combining these criteria, HOMER enables the identification of the most optimal energy configuration in terms of performance, cost, and environmental impact.

C. Description of Study Sites and Meteorological Conditions

To assess the suitability of hybrid systems in off-grid areas, we conducted a comparative study based on numerical simulations. This study focused on two distinct sites with differing climatic and socioeconomic characteristics. Meteorological data, population energy needs, and costs of various technologies were considered in our models.

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Antanimora Sud (-24.8167°S, 45.6667°E, 298m) has a tropical savanna climate with a dry winter (Aw) with annual precipitation of 1329.7 mm and an average temperature of 23.8°C. This region in southern Madagascar is characterized by savannas and distinct seasons.

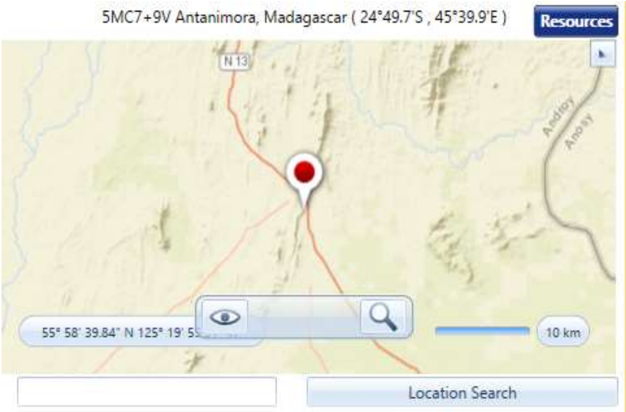

Fig. 1. Geographic coordinates of Antanimora Sud.

Toamasina (18°08′57″S, 49°24′08″E, 12 m) has a tropical equatorial climate (Af) characterized by high and stable average temperatures throughout the year (around 24.1°C). Precipitation is abundant and well-distributed throughout the year, reaching an annual average of 2751 mm.

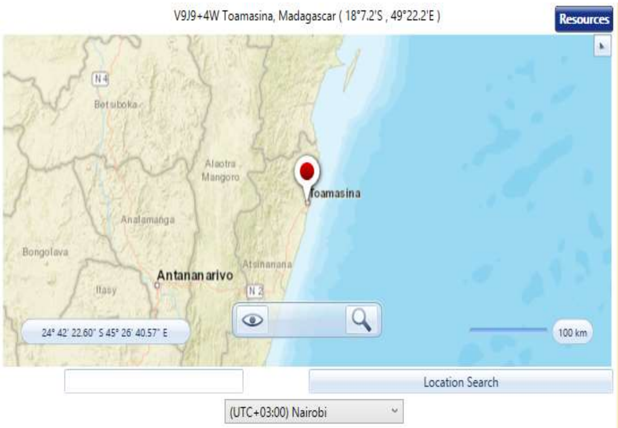

Fig. 2. Geographic coordinates of Antanimora Sud.

D. Simulated Scenarios

For both sites, three system configurations were simulated: standalone PV, standalone generator, and a hybrid system. To assess the impact of different factors, the following scenarios were considered:

- Climatic Conditions: Simulations were conducted with varying weather conditions to evaluate system performance under different climatic scenarios.
- Load Levels: Simulations with varying nominal loads were performed to determine the power threshold at which a hybrid system becomes economically viable and to analyze the impact of daily load profiles on system performance.
- Economic Factors: Sensitivity analysis was conducted to assess the impact of variations in fossil fuel prices and discount rates.

E. Modeling

This study employs HOMER Pro as the simulation software due to its ability to accurately and efficiently model and optimize hybrid energy systems.

1. Simulation Parameters:
   - Electrical Loads: Loads are characterized by their nominal power and specific daily load profiles.
   - Technologies: Solar panels, batteries, and generators are modeled with their respective technical characteristics (peak power, efficiency, capacity, etc.).
   - Economic Factors: Investment and operating costs, energy costs, discount rate, and project lifetime are integrated into the modeling.
2. Multiple Simulation Scenarios and Optimal Configuration Identification
   - Scenario Analysis: Simulations were conducted with varying load powers to determine the economic viability threshold of a hybrid system. Sensitivity analysis was performed by varying parameters such as fuel price, discount rate and CO_2 emission costs to assess the system's robustness.
   - Optimal Configuration Identification: Based on the simulation results, the optimal system configuration for each site was identified. This involved selecting the system configuration that minimized the NPC and COE while meeting the specified energy demand and reliability requirements.

F. Assessing the impact of optimizations on economic and environmental performance

A comparative analysis was conducted to evaluate the impact of different optimized configurations on the system's economic and environmental performance. A conventional generator set served as the baseline system. The optimized configurations were compared to this baseline to quantify improvements in operating costs and greenhouse gas emissions. This approach allows for the identification of the most effective configurations and the rationale behind the selected technical choices.

IV. RESULTS AND DISCUSSION

This section presents the results obtained from the simulations conducted using HOMER Pro. The inputs used for these simulations, including climatic data, load profiles, and system component specifications. The following subsections present the results for each of the simulated scenarios, focusing on the key performance indicators defined in Section III.

The simulation consists of three steps:

- Sensitivity to climatic conditions: An identical load profile and materials are applied to two sites with varying meteorological data;
- Sensitivity to load variations: The load profile of each site is adjusted between 100 and 150 kWh/day to evaluate the impact on costs (NPC and COE) and system configuration;
- *Simulation 3: Sensitivity to diesel prices and discount rates*

A. Simulation 1: Sensitivity to Climatic Conditions

1. Input parameters

The HOMER simulations were based on a comprehensive set of input parameters that accurately characterized the system and its environment. These parameters included meteorological data, load profiles, and component specifications. By meticulously defining these inputs, we were able to assess the technical and economic feasibility of various system designs and identify the optimal solution tailored to specific needs.

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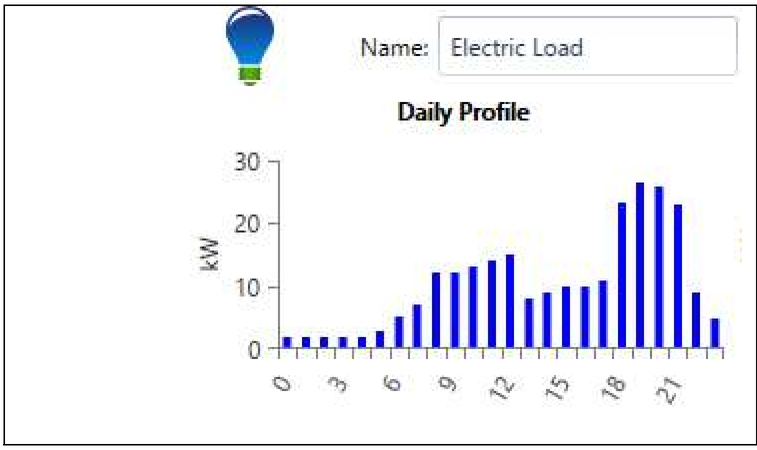

Metric	Baseline	Scaled
Average (kWh/day)	251.2	45
Average(kW)	10.47	1.88
Peak (kW)	44.49	7.97
Load factor	.24	.24

Fig. 1. Daily Profile for both sites

a. Load profiles

The daily load profile, as depicted in Figure 1, exhibits a pronounced peak in electricity demand during the evening hours (between 18:00 and 21:00), corresponding to residential lighting and appliance usage. This is followed by a significant decrease in demand during the overnight period. Key metrics include a daily energy consumption of 45 kWh/day, an average power of 1.88 kW, a peak demand of 7.97 kW, and a load factor of 0.24. These values are scaled from an initial baseline scenario with higher consumption. The load type is alternating current (AC), typical of residential electrical systems. Both sites have the same daily load profile.

b. Climatic data

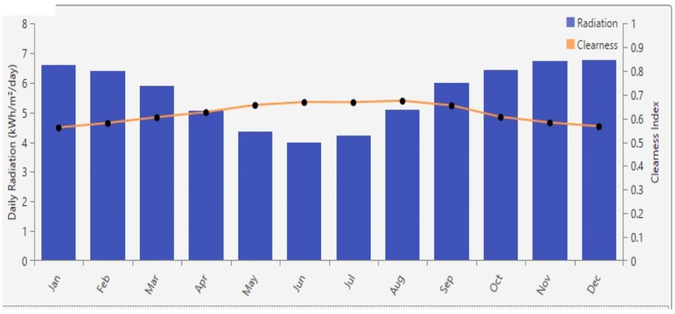

Fig.2. Climatic data for Antanimora Sud

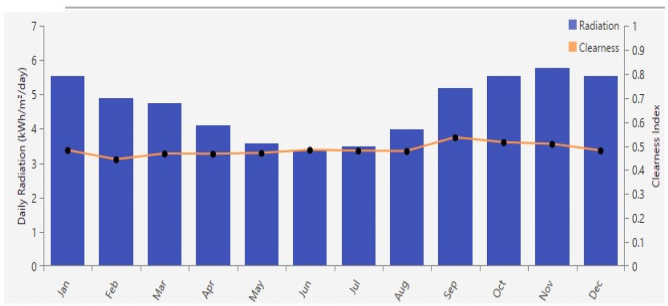

Fig.3. Climatic data for Toamasina

June emerged as the month with the lowest solar irradiance for both sites. Toamasina experienced a more pronounced solar deficit compared to Antanimora Sud, with average daily solar irradiance values of 3.36 kWh/m²/day and 3.99 kWh/m²/day, respectively.

c. Equipment characteristics

Both systems share a similar basic design. As illustrated in Fig. 4, the system comprises a combination of solar power and a diesel generator. Solar panels capture sunlight and convert it into electricity, while a battery stores excess energy during periods of surplus. When solar power is insufficient, the diesel generator activates to meet the remaining energy demand.

The system is configured to meet a daily energy demand of 45 kWh and a peak demand of 7.18 kW. In HOMER, the off-grid hybrid system is simulated using a parallel configuration. The diesel generator is directly connected to the AC bus, while the

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photovoltaic system and battery are linked to a DC bus. A bidirectional converter facilitates the interface between these two buses, functioning as a rectifier to charge the battery from the AC grid or as an inverter to inject energy from the battery or solar panels into the AC bus. This configuration enables the load to be powered simultaneously by multiple energy sources.

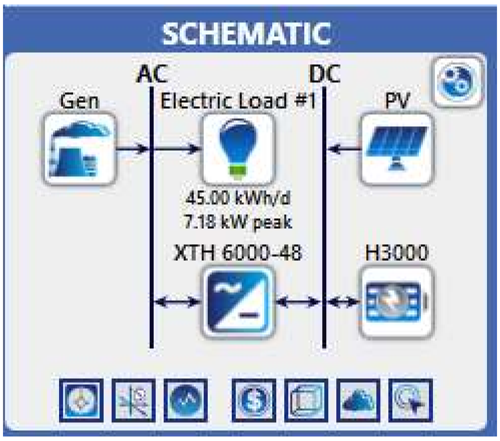

Fig.4. Homer Pro Configuration

2. *Optimal Energy Configuration for Systems*

a. *Optimal Energy Configuration for Systems in Toamasina*

Fig.5 illustrates the best-suited energy system for a 45 kWh/day load, as determined through a comparative analysis of different configurations.

Architecture					Cost				System		Gen				
PV (kW)	Gen (kW)	H3000	XTH 6000-48 (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours	Production (kWh)	Fuel (L)	O&M Cost ($/yr)	Fuel Cost ($/yr)
26.3		24	6.81	CC	$53,679	$0.253	$830.64	$42,941	100	0					
18.3	8.00	24	6.24	LF	$55,337	$0.261	$862.62	$44,186	98.5	112	118	250	112	28.3	112
105	8.00		3.14	CC	$94,551	$0.445	$6,536	$10,052	32.8	4,345	3,895	11,034	4,345	935	4,345
	8.00			CC	$133,845	$0.630	$10,168	$2,400	0	7,474	6,935	18,533	7,474	1,664	7,474
	8.00	24	0.458	LF	$166,076	$0.782	$10,223	$33,916	0	7,178	6,903	17,340	7,178	1,657	7,178

Fig. 5. Five most cost-effective configurations for Toamasina for a 45 kWh/day load

Results indicate that, among the configurations studied, the standalone photovoltaic system (26.3 kWp, $53,679) was more cost-effective than the hybrid system (18.3 kWp and an 8 kW generator, $55,337). This finding suggests that, for the specific conditions of Toamasina, a standalone PV system is the most economically viable option.

b. *Optimal Energy Configuration for Systems in Antanimora Sud*

Fig. 6 showcases the optimal energy system for a 45 kWh/day load, identified through a comparative analysis of various configurations.

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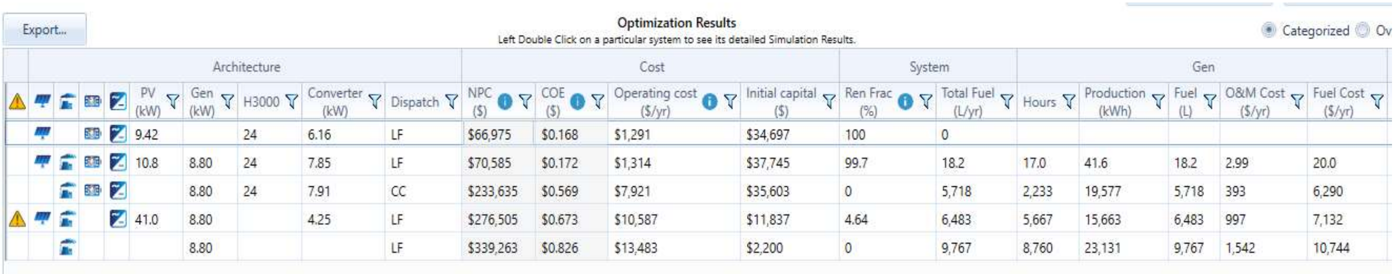

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Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.

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PV (kW)	Gen (kW)	H3000	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours	Production (kWh)	Fuel (L)	O&M Cost ($/yr)	Fuel Cost ($/yr)
Architecture					Cost				System		Gen				
9.42		24	6.16	LF	$66,975	$0.168	$1,291	$34,697	100	0					
10.8	8.80	24	7.85	LF	$70,585	$0.172	$1,314	$37,745	99.7	18.2	17.0	41.6	18.2	2.99	20.0
	8.80	24	7.91	CC	$233,635	$0.569	$7,921	$35,603	0	5,718	2,233	19,577	5,718	393	6,290
41.0	8.80		4.25	LF	$276,505	$0.673	$10,587	$11,837	4.64	6,483	5,667	15,663	6,483	997	7,132
	8.80			LF	$339,263	$0.826	$13,483	$2,200	0	9,767	8,760	23,131	9,767	1,542	10,744

Fig. 6. Five Most Economical Configurations for Antanimora Sud at 45 kWh/day load

Results show that, among the configurations studied, the standalone photovoltaic system (9.42 kWp, $66,975) was more cost-effective than the hybrid system (10.8 kWp and an 8.80 kW generator, $70,585). This suggests that, for the specific conditions of Antanimora Sud, a standalone PV system is the most economically viable option.

Under different climatic conditions, with the same load profile, the optimal configurations are different for the two experimental sites.

B. Simulation 2: Sensitivity to load variations

1. Optimization results

Tables I and II summarize the optimal configurations, that minimizes the total cost while meeting the energy needs, for different daily consumption levels in Toamasina and Antanimora Sud, respectively. Table III provides a comparative analysis of the two sites.

Key abbreviations used in the tables include: NPC (Net Present Cost), COE (Cost of Energy), OP (Operating Cost), IC (Initial Capital), and Ren. Frac. (Renewable Fraction). The configurations include photovoltaic (PV), batteries (BAT), generators (GE), and converters (CONV).

Table I. Optimal Energy Configurations for Toamasina

Daily Consumption (kWh/d)	Configurations	NPC ($)	COE ($/kWh)	OP($)	IC($)	Ren. Frac. (%)	Total Fuel (L/y)
45	PV+BAT+CONV	136,425	0.643	5,693	62,826	100	0
	GE	194,427	0.915	14,905	1584	0	9,763
	PV+GE+CONV	194,332	0.915	14,907	1,625	0	9,763
	PV+GE+BAT+CONV	217,239	1.02	12,459	56,173	1.01	6,990
	GE+BAT+CONV	225,789	1.06	13,207	55,061	0	7,929
60	PV+BAT+CONV	194,085	0.686	9,575	70,303	100	0
	GE	263,818	0.932	20,240	2,160	0	13,242
	PV+GE+CONV	263,904	0.932	20,243	2,215	0	13,242
	PV+GE+BAT+CONV	270,807	0.957	16,526	57,168	0	9,492
	GE+BAT+CONV	280,859	0.992	17,418	55,693	0	10,672
80	PV+GE+BAT+CONV	178,504	0.473	8,586	67,508	91	1,111
	PV+BAT+CONV	248,443	0.659	9,638	123,844	100	0
	GE+BAT+CONV	312,396	0.828	15,360	113,827	0	9,769

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	GE	351,758	0.932	26,987	2,880	0	17,656
	PV+GE+CONV	352,635	0.934	27,042	3,045	0	17,631
100	PV+GE+BAT+CONV	200,575	0.425	10,336	66,957	68.3	4,075
	GE+BAT+CONV	318,184	0.674	15,676	115,531	0	12,091
	PV+BAT+CONV	320,647	0.680	11,009	178,326	100	0
	GE	359,985	0.763	27,568	3,600	0	8,760
	PV+GE+CONV	361,166	0.765	27,643	3,805	0	8,760
120	PV+GE+BAT+CONV	235,300	0.416	12,873	68,878	63.8	5,623
	GE+BAT+CONV	318,649	0.563	20,025	59,774	0	15,508
	PV+BAT+CONV	408,777	0.722	13,397	235,586	100	0
	GE	431,982	0.763	33,082	4,320	0	26,484
	PV+GE+CONV	433,400	0.763	33,172	4,565	0	26,447
140	PV+GE+BAT+CONV	271,450	0.414	15,466	71,518	63	6,730
	GE+BAT+CONV	365,886	0.554	23,600	60,793	0	18,186
	PV+BAT+CONV	422,887	0.641	17,952	190,806	100	0
	GE	503,979	0.763	38,595	5,040	0	30,899
	PV+GE+CONV	505,625	0.765	38,700	5,327	0	30,854
150	PV+GE+BAT+CONV	289,634	0.409	16,770	72,839	62.8	7,285
	GE+BAT+CONV	390187	0.551	25452	61162	0	19766
	PV+BAT+CONV	456839	0.646	20240	195189	100	0
	GE	539977	0.763	41352	5400	0	33106
	PV+GE+CONV	541747	0.765	41465	5760	0	33058

Table II. Optimal Configurations for Various Daily Consumption Levels in Antanimora Sud

Daily Consumption (kWh/d)	Configurations	NPC ($)	COE ($/kWh)	OP($)	IC($)	Ren. Frac. (%)	Total Fuel (L/y)
45	PV+BAT+CONV	66,975	0.168	1,291	34,697	100	0
	PV+ GE+BAT+CONV	70,585	0.172	1,314	37,745	99.7	18.2
	GE+BAT+CONV	233,635	0.569	7,921	35,603	0	5,718
	PV+ GE+BAT+CONV	276,505	0.673	10,587	11,837	4.64	6,483
	GE	339,263	0.826	13,483	2200	0	9,767
100	PV+BAT+CONV	118,717	0.430	1,294	108,564	100	0
	GE	160,308	0.560	19,674	6,000	0	22,201
	PV+GE+CONV	160,312	0.560	19,674	6,003	0	22,201
	GE+BAT+CONV	163,037	0.570	16,102	36,747	0	18,250
	PV+GE+BAT+CONV	170,756	0.596	14,268	58,849	0	15,777

120	GE+BAT+CONV	129,008	0.376	11,581	38,178	0	15,067
	PV+BAT+CONV	145,275	0.439	1,777	131,336	100	0
	GE	192,370	0.560	23,609	7,200	0	26,641
	PV+GE+CONV	192,374	0.560	23,609	7,204	0	26,641
	PV+GE+BAT+CONV	198,834	0.579	17,137	64,429	0	18,994
140	GE+BAT+CONV	143,726	0.359	13,299	39,418	0	17,377
	PV+BAT+CONV	172,005	0.445	1,276	162,001	100	0
	GE	224,431	0.560	27,544	8,400	0	31,081
	PV+GE+CONV	224,437	0.560	27,544	8,405	0	31,081
	PV+GE+BAT+CONV	225,873	0.564	19,873	70,008	0	22,060
150	GE+BAT+CONV	152,252	0.355	14,310	40,017	0	18,602
	PV+GE+BAT+CONV	171,424	0.399	5,875	125,347	78.8	4,950
	PV+BAT+CONV	182,432	0.440	1,480	170,826	100	0
	GE	240,462	0.560	29,511	9,000	0	33,301
	PV+GE+CONV	240,468	0.560	29,512	9,005	0	33,301

For the Antanimora site, solar photovoltaic systems appear to be the most suitable solution for low consumption levels, while systems with a generator and battery are more efficient for high consumption levels according to the criteria retained in this study.

2. Impact of Consumption and Geographic Factors on Optimal Energy System Configurations

The table III provides optimal configurations, NPC and COE for different consumption levels (C) in two locations: Toamasina and Antanimora.

Table III. Optimal Energy Configurations for Toamasina and Antanimora Sud: A Comparative Analysis

Site	Consumption C (kWh/day)	Optimal Configuration	NPC ($)	COE ($/kWh)	Renewable Fraction (%)
Toamasina	45≤ C< 80	PV+BAT+CONV	136,426 - 194,085	0.64-0.686	100
Toamasina	80≤ C≤ 150	PV+GE+BAT+CONV	178,504 – 289,634	0.473 – 0.409	62.8 - 91
Antanimora	45≤ C≤100	PV+BAT+CONV	66,975 - 118,717	0.168 - 0.430	100
Antanimora	100< C≤ 150	GE+BAT+CONV	129,008-152,252	0.376-0.355	0

NPC and Consumption :

- Direct Relationship: As daily consumption increases, the NPC also rises. This is because larger systems are necessary to meet the increased energy demand, leading to higher upfront costs.
- Decreasing COE: Despite the higher NPC, the COE tends to decrease with higher consumption levels. This is likely due to economies of scale, where larger systems can benefit from more efficient component utilization and potentially lower unit costs.

Optimal Configuration and Consumption :

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- Low Consumption: For lower consumption levels, both Toamasina and Antanimora benefit from similar configurations (PV+BAT+CONV), highlighting the potential of solar energy for smaller energy needs.
- High Consumption: For higher consumption levels:
    - Toamasina: The optimal configuration shifts to PV+GE+BAT+CONV, indicating a need for both solar energy and generators to meet the increased demand.
    - Antanimora: The optimal configuration becomes GE+BAT+CONV, suggesting a stronger reliance on generators.

Load Profiles and Optimal Configurations:

- Site-Specific Differences: The optimal configurations vary between Toamasina and Antanimora, even for similar consumption levels. This suggests that factors like local solar irradiance, grid reliability, and energy costs influence the optimal system design.
- Thresholds: The "threshold" consumption levels where the optimal configuration changes are different for the two sites, further emphasizing the site-specific nature of optimal solutions.

Overall, the analysis suggests that while higher consumption levels generally lead to higher NPC, the COE can be reduced through economies of scale. The optimal system configuration depends on both consumption level and site-specific factors.

C. *Simulation 3: Sensitivity to diesel prices and discount rates*

To assess the robustness of our optimal system configurations and understand the impact of economic uncertainties, we conducted a sensitivity analysis. This analysis focused on the effects of varying discount rates and diesel fuel prices on the optimal energy system design. As a case study, we will present the results obtained for the Antanimora Sud site.

Figures 7 and 8 illustrate the optimized economic configurations and the sensitivity of system costs and performance to changes in diesel prices and discount rates for a 150 kWh/day consumption.

Export... | Optimization Results | Left Double Click on a particular system to see its detailed Simulation Results. | Categorized | Ove

Architecture					Cost				System		Gen					
PV (kW)	Gen (kW)	H3000	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours	Production (kWh)	Fuel (L)	O&M Cost ($/yr)	Fuel Cost ($/yr)
	30.0	24	23.6	CC	$152,252	$0.355	$14,310	$40,017	0	18,602	2,193	63,247	18,602	1,974	9,301
28.4	30.0	24	22.9	LF	$171,424	$0.399	$5,875	$125,347	78.8	4,950	1,317	11,616	4,950	1,185	2,475
36.3		48	28.9	LF	$182,432	$0.440	$1,480	$170,826	100	0					
	30.0			LF	$240,462	$0.560	$29,511	$9,000	0	33,301	8,760	78,872	33,301	7,884	16,650
0.000125	30.0		0.409	CC	$240,468	$0.560	$29,512	$9,005	0	33,301	8,760	78,872	33,301	7,884	16,650

Fig.7 Five most cost-effective configurations for Antanimora Sud at 150 kWh/day load

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Export... Export All... **Sensitivity Cases** Left Click on a sensitivity case to see its Optimization Results. Compare Economics Column Choices...

Sensitivity		Architecture					Cost				System		Gen	
NominalDiscountRate (%)	Diesel Fuel Price ($/L)	PV (kW)	Gen (kW)	H3000	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours	Production (kWh)
12.0	0.500		30.0	24	23.6	CC	$152,252	$0.355	$14,310	$40,017	0	18,602	2,193	63,247
3.00	0.500	36.3		48	28.9	LF	$202,783	$0.220	$1,835	$170,826	100	0		
6.00	0.500	17.2	30.0	24	15.1	CC	$180,345	$0.258	$6,953	$91,458	44.7	9,094	1,160	30,297
12.0	1.00	18.6	30.0	24	15.9	CC	$179,371	$0.418	$10,683	$95,583	48.1	8,526	1,082	28,442
3.00	1.00	36.3		48	28.9	LF	$202,783	$0.220	$1,835	$170,826	100	0		

Fig. 8 Sensitivity of Operating Costs and Greenhouse Gas Emissions to Discount Rate and Fuel Price

1. Influence of Discount Rate :

   - Low Discount Rate (3%): Strongly favors configurations with a high renewable energy component (PV+BAT+CONV). This is because a low discount rate places a higher value on long-term savings from solar electricity generation.
   - High Discount Rate (12%): Leans towards configurations with a larger share of diesel generators (GE+BAT+CONV). A high discount rate prioritizes short-term investments where diesel generators can be more competitive.

2. Influence of Diesel Price :

   - High Diesel Price ($1/L): Encourages the adoption of renewable solutions to reduce fossil fuel dependency and control operating costs.
   - Low Diesel Price ($0.5/L): Makes diesel generators more competitive, even with a low discount rate.

3. Optimal Configuration (GE+BAT+CONV):

While the indicated optimal configuration is GE+BAT+CONV, the sensitivity analysis shows that this configuration is not always the most advantageous depending on economic conditions. For scenarios with a low discount rate and/or a high diesel price, a configuration dominated by renewables (PV+BAT+CONV) becomes more attractive.

4. Discussion

The results of this analysis highlight the importance of considering economic factors when selecting an optimal energy configuration. Investment decisions in energy systems are influenced by :

- Time Value of Money: a low discount rate favors long-term investments in renewable energy.
- Fossil Fuel Prices: an increase in diesel prices makes renewable solutions more competitive.
- Energy Policies and Financial Incentives: policies that favor renewable energy can alter technological choices.

In conclusion, sensitivity analysis helps identify the most robust configurations and better understand the trade-offs between investment costs, operating costs, and environmental impact. For the Antanimora Sud site, a flexible approach is recommended, allowing the system configuration to adapt to changes in energy prices and policies.

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D. Comparative analysis

This table (Table IV) presents a comparative analysis of the five optimized energy system configurations shown in Fig. 7, numbered from 1 to 5 based on their cost-effectiveness, for a daily consumption of 150 kWh/day, with a conventional generator (GE) set as the baseline reference.

Table IV. Economic and Environmental Assessment of Various Energy System Configurations for a 150 kWh/day Load in Antanimora Sud

	1-4	2-4	3-4
ECONOMICS			
Present Worth($)	88,210	69,038	58,030
Annual Worth ($/y)	11,247	8,802	7,399
Return on Investissement(%)	43.6	16	13.1
Internal Rate of Return (%)	52.4	20.2	16.9
Simple Payback (y)	1.8	4.78	5.70
Discounted Payback(y)	2.13	6.98	9.91
EMISSION			
Carbon Dioxide(kg/y)	48,693	12,956	
Carbone Monoxide (kg/y)	307	81.7	
Unburned Hydrocarbons(kg/y)	13.4	3.56	
Particulate Matter(kg/y)	1.86	0.495	
Sulfur Dioxide(kg/y)	119	31.7	
Nitrogen Oxides(kg/y)	288	76.7	

1. *Economic Performance:*

- Present Worth (PW): Configuration 1 (GE+BAT+CONV) has the lowest PW, indicating the lowest overall cost over the project's lifetime;
- Annual Worth (AW): Configuration 1 also has the lowest AW, suggesting the lowest annualized cost.
- Return on Investment (ROI) and Internal Rate of Return (IRR): Configuration 1 offers the highest ROI and IRR, indicating a stronger financial return;
- Payback Period: Configuration 1 has the shortest payback period, meaning the initial investment is recovered more quickly.

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2. *Environmental Performance*

Configurations with higher renewable energy fractions (Configurations 2 and 3) have significantly lower emissions of carbon dioxide, carbon monoxide, hydrocarbons, particulate matter, sulfur dioxide, and nitrogen oxides.

Gas emissions are directly proportional to the amount of fuel consumed by the system, and they decrease significantly as the proportion of renewable energy increases.

3. *Renewable Energy Fraction*

Configurations 2 and 3 demonstrate higher renewable energy fractions, indicating a greater reliance on renewable sources.

4. *Trade-offs:*

- There is a trade-off between economic performance and environmental impact. Configurations with lower emissions generally have higher initial costs and lower financial returns.
- The optimal configuration depends on the specific priorities of the decision-maker. For example, a focus on environmental sustainability might favor Configuration 3, while a focus on economic efficiency might favor Configuration 1.

5. *Comparative Analysis:*

- Configurations 1-4: Configuration 1 consistently outperforms the others in terms of economic metrics. However, it has lower environmental performance.
- Configurations 2-4: Configuration 2 offers a good balance between economics and emissions, while Configuration 3 focuses on environmental performance but has higher costs.
- Configuration 4 (GE): The standalone generator has the highest emissions and lowest renewable energy fraction, making it the least desirable option from an environmental perspective.

Overall, the analysis suggests that hybrid systems combining renewable energy sources (solar PV and batteries) with generators can offer a more sustainable and cost-effective solution compared to standalone generators. The optimal configuration depends on specific priorities and the relative importance of economic and environmental factors.

V. CONCLUSION

Our study addresses a critical question for Madagascar's energy future: In this tropical country with high solar potential, are hybrid systems a necessity for optimal energy provision, or can standalone systems such as photovoltaic or diesel generators also be optimal among many viable alternatives?

Based on simulations using HOMER software, our findings provide valuable insights while also pointing towards the need for more comprehensive analysis in the future.

Key findings from our current study include:

- The optimal energy solution varies significantly based on local factors such as solar irradiation, energy demand patterns, equipment costs, fuel price fluctuations, and discount rates.
- In numerous scenarios, hybrid systems offer a superior balance of reliability, flexibility, and cost-effectiveness compared to standalone alternatives.
- In certain contexts, particularly areas with exceptional solar resources and relatively stable energy demands, standalone photovoltaic systems can be the optimal choice.

- The Net Present Cost and Cost of Energy of different systems vary based on local conditions, with hybrid systems often presenting a better long-term economic case.

Based on these findings, we conclude that while hybrid systems are not an absolute necessity in every situation, they represent a crucial component in Madagascar's potential energy portfolio. Their ability to combine the strengths of renewable and conventional energy sources makes them indispensable in many contexts, particularly in regions with variable energy needs or less predictable solar resources.

However, our study also highlights the need for a more comprehensive approach to energy system evaluation. As a key perspective for future research, we propose the implementation of a multi-criteria analysis that would evaluate energy systems across technical, economic, environmental, and social dimensions. This approach would provide a more nuanced understanding of the optimal energy solutions for different regions of Madagascar.

Recommendations for future research and policy directions include:

- Developing and implementing a comprehensive multi-criteria analysis framework for energy system evaluation in Madagascar.
- Conducting detailed site-specific assessments using this multi-criteria framework before implementing any energy solution.
- Investing in comprehensive energy mapping that incorporates multiple criteria to identify optimal system types for different regions.
- Developing flexible regulatory frameworks that encourage diverse energy solutions, including hybrid systems where appropriate.
- Prioritizing capacity building to ensure proper management and maintenance of diverse energy systems.
- Exploring innovative financing mechanisms to overcome initial cost barriers, especially for hybrid systems.
- Establishing a monitoring and evaluation system to continuously assess the performance of implemented solutions across multiple criteria.

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