



Design, sizing, and feasibility analysis of a hybrid renewable generation system for the self-sufficiency of an off-grid house

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Original Scientific Paper

Submitted: 07 July 2026

Accepted: 26 Sept 2026

Published: 30 Sept 2026

Abstract

Rural isolation from national electricity grids represents a persistent infrastructure challenge in Mediterranean mountainous regions, where isolated dwellings have traditionally depended on generators with prohibitive environmental and economic costs. This study proposes a modular engineering framework for the design and sizing of hybrid off-grid renewable generation systems, applied as a case study to a residential property in El Pla de La Llacuna (Villalonga, Valencia, Spain). The methodology develops a decoupled catalogue of four independent energy modules – solar photovoltaic (PV), micro-wind, geothermal, and electrochemical storage – each governed by strict technical boundary conditions that filter site suitability. The framework was applied through a multi-step process: resource characterisation using the PVGIS-SARAH3 database and hyper-local AVAMET meteorological data; load profile construction via a bottom-up appliance inventory; and iterative system sizing validated through computational simulation. Three energy supply scenarios were simulated and benchmarked against a 100% fossil-fuel baseline. The results demonstrate that a hybrid solar-wind configuration comprising 8 photovoltaic panels (4.28 kWp), 6 LiFePO₄ batteries (28.8 kWh), and a 10 kW Vertical Axis Wind Turbine (VAWT) constitutes the optimal solution for this site, achieving total annual energy self-sufficiency with a capital expenditure of €12,328, a net present value (NPV) of €337,406, a return on investment (ROI – return on investment) of 34.07, and a payback period of 0.323 years. Geothermal exploitation was rejected due to geological and logistical constraints, while continuous wind generation was discarded as a primary source due to insufficient mean velocities, though transient gusts up to 73.4 km/h were successfully harvested as a winter supplementary resource.

Keywords: off-grid systems; hybrid renewable energy; photovoltaic sizing; VAWT; LiFePO₄ storage; modular design; energy self-sufficiency; PVGIS; rural electrification

1. Introduction

The global transition toward decentralised, renewable energy systems has shifted from theoretical aspiration to technical and environmental necessity, particularly in geographically isolated regions. In the Mediterranean basin, and specifically within mountainous inland territories, residential properties frequently face a critical infrastructure challenge: the complete absence of a reliable connection to the national electricity grid. Historically, these isolated off-grid dwellings have depended on internal combustion generators to meet energy demands – a model that entails severe drawbacks, including high operational costs, logistical challenges in fuel supply, noise pollution, and significant greenhouse gas emissions.



Theme	Key finding	Population / system focus	Citations
Baseline architecture	The most established off-grid residential architecture is PV + wind + battery , typically coordinated through inverter and charge-control components; some studies add diesel, hydrogen, or fuel cells to increase autonomy and reliability.	Off-grid houses, remote communities, rural electrification systems	(Akinyele, Rayudu, Nair, 2016); (Mohammadnezami et al., 2015); (Sahu, Jena, Sahoo, 2021), (Engin, 2013), (Jadhav, Patil, 2020), (Al-Quraan, Al-Mhairat, 2024), (Rathod, Balaji, 2025), (Ahmad, Farzaneh, 2024)
Design logic	Hybridisation usually improves reliability and renewable contribution relative to single-source systems, but the best mix depends on local solar-wind complementarity and the household load profile.	Residential and rural hybrid energy systems	(Rathod, Balaji, 2025), (Nizam et al., 2025), (Bicks, 2021), (Behmounesi et al., 2024), (Tutkun, Çelebi, Bozok, 2017)
Resource assessment	Recent sizing studies increasingly use PVGIS, Meteonorm, NASA POWER, GIS screening, and TMY/hourly weather series rather than simple averages.	Off-grid PV-wind sizing studies	(AbdelHadi et al., 2025), (Alotaibi, Alturki, 2025), (Petrollese, Seche, Cocco, 2019), (Mayer, Szilágyi, Gróf, 2020)
Wind/PV conversion methods	Annual yield estimates often convert weather inputs using module-plane irradiation models for PV and hub-height extrapolation plus turbine power curves for wind.	Simulation-based hybrid system sizing	(Petrollese, Seche, Cocco, 2019), (Mayer, Szilágyi, Gróf, 2020), (Chen, Aidong Yang, Bañares-Alcántara, 2021)
LiFePO4 storage	LiFePO4 is increasingly preferred for off-grid storage because of long cycle life, high efficiency, deep-discharge tolerance, thermal stability, and fewer replacements than lead-acid options.	Off-grid PV and hybrid storage systems	(Shimomura, Mochizuki, Takano, 2016), (Chen et al., 2021), (Eteiba et al., 2018), (Layadi et al., 2023), (Abed, Maheri, 2025)
Battery caveats	LiFePO4 performance still depends strongly on temperature, charge/discharge rate, SOC window, and degradation assumptions.	Stationary battery studies, microgrids, off-grid storage	(Zhao et al., 2020), (Abd El-Sattar, Kamel, Hassan, 2025), (Wen, Zhao, Zhang, 2020), (Yang et al., 2025)
Sizing methods	HOMER, GA, PSO, MATLAB/Simulink, and multi-objective metaheuristics are the dominant sizing approaches, usually minimising NPC, TAC, COE/LCOE while enforcing LPSP/DPSP/autonomy constraints.	Off-grid houses and small communities	(He et al., 2023), (Fares, Fathi, Mekhilef, 2022), (Thirunavukkarasu, Lala, Sawle, 2023), (Gicevskis et al., 2021), (Li, 2019), (Forrousso et al., 2024), (Das, 2020)



Feasibility metrics	The standard feasibility indicators are LCOE/COE, NPC, reliability, unmet load or LPSP, renewable fraction, autonomy, and sensitivity analysis.	Rural electrification case studies	(Nguyen et al., 2024), (Fosso Tajouo, Tiam Kapen, Djanna Koffi, 2023), (Viridyet al, 2026), (Diyono et al, 2026), (Ghaziasgar, Pourfayaz, Vaziri Rad, 2025)
Central trade-off	Higher self-sufficiency and stricter reliability generally require more storage and higher capital cost; full off-grid autonomy is often more expensive than grid-connected or backup-assisted options.	Off-grid vs on-grid / diesel-assisted comparisons	(Ahmad, Zhang, 2021), (Bullen et al., 2025), (Caglayan, 2025), (Rajbongshi, Borgohain, & Mahapatra, 2017), (Kolhe, Ranaweera, & Gunawardana, 2013)

A bibliometric analysis of 44 peer-reviewed documents retrieved from ScienceDirect (2021–2026) using VOSviewer v.1.6.20 (Van Eck, Waltman, 2014) for co-occurrence analysis identified three strategic research pillars sustaining the development of decentralised systems: thermal and geothermal cluster technologies, building-integrated energy efficiency, and the photovoltaic-storage backbone underpinning electrical autonomy (*Figure 1*). These pillars highlight the current knowledge gap: the lack of replicable, modular design methodologies adaptable to heterogeneous rural environments.

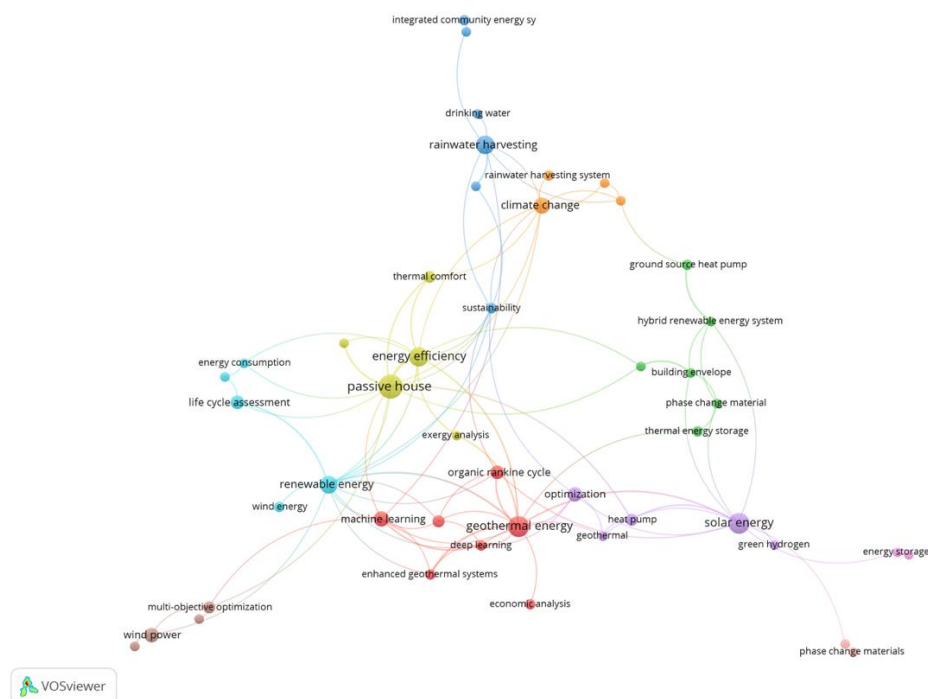


Figure 1. Bibliometric network map of keyword co-occurrences in off-grid hybrid energy literature.

Source: Own elaboration based on data extracted from ScienceDirect via VOSviewer (2026).

This study addresses that gap by developing a modular engineering framework composed of four independent energy modules – Solar Photovoltaic (Module A), Micro-Wind Generation (Module B), Geothermal Systems (Module C), and Electrochemical Storage (Module D) – each governed by strict technical entry thresholds. Unlike traditional single-point engineering solutions, the proposed catalogue is designed to be adaptable and scalable, enabling different configurations to be assembled to suit the specific topography, climate, and budget of any given rural site. To demonstrate the framework's



applicability, the methodology is applied to a permanent residential property in El Pla de La Llacuna (Villalonga, Valencia, Spain), a representative case of an isolated Mediterranean mountain dwelling.

It is hypothesised that a hybrid photovoltaic-wind configuration, sized and optimised using the modular filtering methodology, can achieve complete year-round energy self-sufficiency for the target household, with a more favourable lifecycle cost profile than both conventional fossil-fuel baselines and purely solar renewable alternatives.

2. Methodology

The methodology is structured in four sequential phases: modular library definition, site resource characterisation, load profile construction, and multi-scenario iterative sizing, data collection for simulation and feasibility study.

2.1 Modular library and entry thresholds

Each energy module was defined with operating principles, selected technology standards, and mandatory boundary conditions for site approval.

Module A (Solar PV): Monocrystalline PERC technology (Wang et al., 2024) was selected for its superior efficiency (20–23%) and low-light performance. The critical entry threshold was defined as a minimum of 2.5 Peak Sun Hours (PSH) in the worst month, as extracted from the PVGIS-SARAH3 database. The structural tilt was mathematically optimised for the winter solstice, using the formula $\beta = \varphi + 15^\circ$, yielding a fixed angle of 54° for the target site's latitude ($\varphi = 38.86^\circ\text{N}$).

Module B (Micro-Wind): A Vertical Axis Wind Turbine (VAWT) architecture was selected over an HAWT for its omnidirectional wind-capture capability under turbulent mountain conditions. The baseline entry threshold required a minimum annual average wind speed of ≥ 3.0 m/s at hub height to qualify as a continuous generation source (Li et al., 2022; Akan, Akan, 2022; Wise et al., 2022).

Module C (Geothermal): Shallow geothermal exploitation via a Ground-Source Heat Pump (GSHP) closed loop was evaluated. Entry criteria included adequate subsoil thermal conductivity ($1.5\text{--}3.0$ W/(m·K)), sufficient surface area for horizontal trench collectors or drilling access for vertical boreholes, and regulatory compliance regarding protected aquifer zones (Tarnawski et al., 2009; Bucci et al., 2017; De León-Ruiz et al., 2022; Maghrabie, Abdeltwab, Tawfik, 2023; Tang et al., 2023; Dong et al., 2024).

Module D (Storage): Lithium Iron Phosphate (LiFePO₄) technology was standardised as the electrochemical storage core, selected for its exceptional cycle life ($> 4,000\text{--}6,000$ cycles at 80% DoD), high round-trip efficiency ($>95\%$), and thermal stability. A 48 V nominal bus architecture was specified to minimise cable losses (Alipour et al., 2020; Kavaliauskas et al., 2023; Roy et al., 2024; Assi, Amer, 2025).

2.2 Site resource characterisation

The target property (*Fig. 2.*) is located at $38^\circ 51' 39.3''$ N, $0^\circ 11' 46.0''$ W, at approximately 600 m above sea level, within the Safor mountain range. Solar resource was quantified via two sequential PVGIS-SARAH3 simulations: a baseline optimised-slope run, and a definitive calibrated run at the engineered 54° angle. Anemometric data were extracted from the AVAMET official network station Vilallonga – La Llacuna / est (separated from the property by a few metres within the same microclimatic boundary layer), covering a full annual cycle from April 2025 to March 2026. Geothermal viability was evaluated through geological characterisation of the local Prebetic subsoil system (AVAMET, n.d.; Martínez del Olmo, 2021).

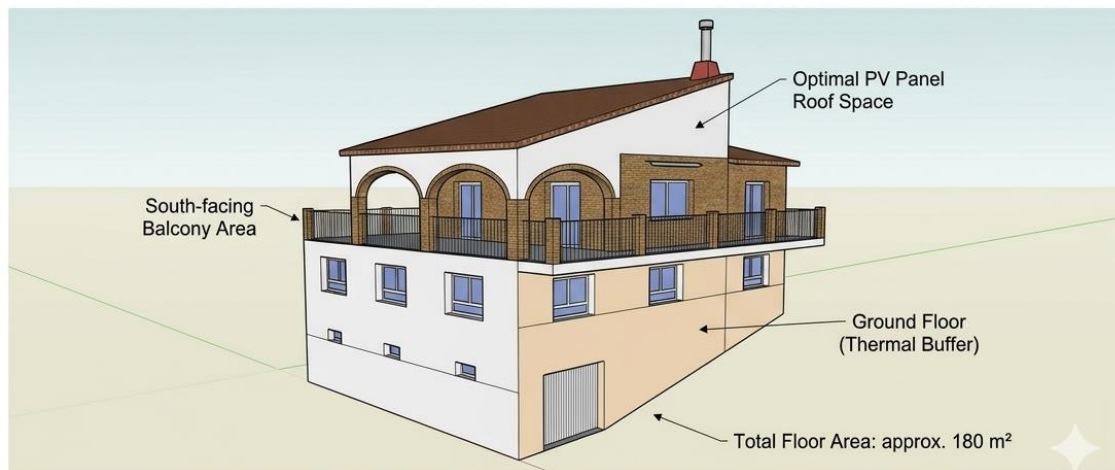


Figure 2. SketchUp 3D digital model and spatial breakdown for solar deployment analysis (Own elaboration, 2026).

2.3 Load profile construction

A dual-methodology approach was employed. First, a top-down municipal baseline was compiled from the Datadis national electricity distribution database (aelēc, n.d.) for Villalonga (April 2025 – March 2026). Second, a bottom-up analytical model was developed from the target household's specific appliance inventory, segmenting demand into a Fixed Consumption Core (7,720 Wh/day) and a Seasonal Variable Load (~900 Wh/day). Twelve monthly seasonal correction factors were applied to capture the full-year environmental variation, generating a definitive average daily consumption of ~8,620 Wh/day. Thermal, cooking, and domestic hot water loads were explicitly excluded from the electrical scope, as they are fully satisfied via biomass and LPG infrastructure (Figure 3).

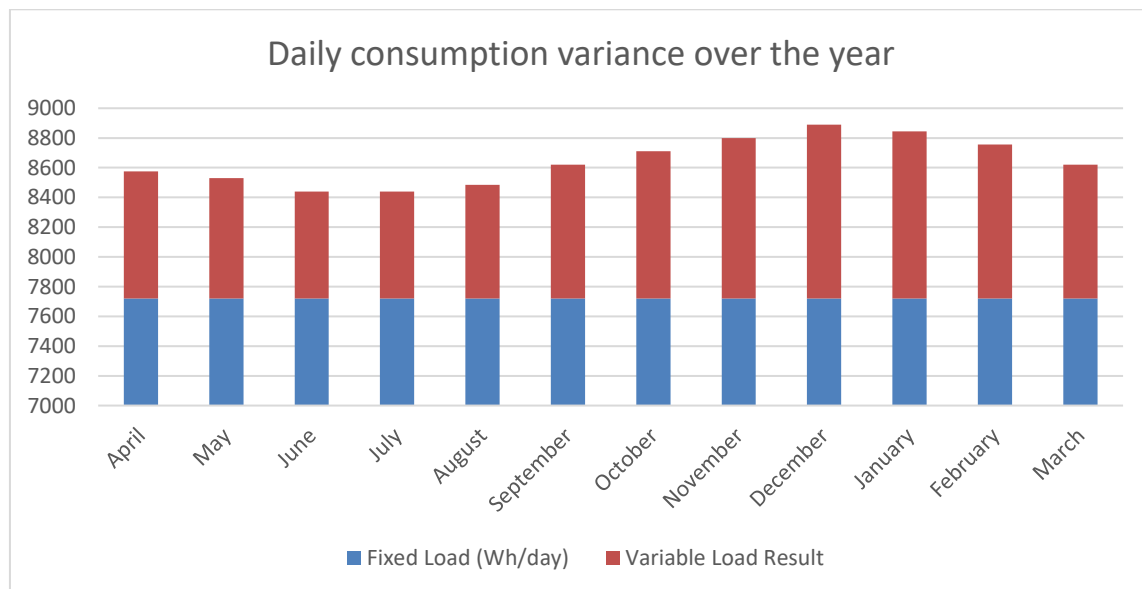


Figure 3. Domestic electrical load curve.

2.4 Scenario sizing and simulation

Four technical scenarios were sized and validated. The primary sizing algorithm used the Worst Month Method, applying the December critical daily demand ($E_d = 8,890$ Wh/day) and local PSH to calculate the required photovoltaic peak power (P_{pv}) and battery capacity (C_n). Computational validation was performed using the PVGIS Off-grid PV simulation tool (EC-JRC, n.d.), with a predefined acceptance criterion of 1%–5% of days with empty battery annually, and a strict maximum



Depth of Discharge (DoD) cutoff of 85% (15% State of Charge (SoC) floor). Financial viability was evaluated over a 10-year lifecycle using Net Present Value (NPV), Return on Investment (ROI), and Time of Return (TOR), applying a 5% discount rate and a 4% annual fuel price escalation to account for Eurozone inflation and carbon pricing trends.

3. Results

This section presents the results from applying the proposed modular engineering framework to the selected off-grid residential case study in Villalonga, Spain. The analysis combines site-specific resource assessment, technical system sizing, computational validation, and financial evaluation to determine the most suitable renewable energy configuration to achieve year-round energy self-sufficiency. The results are interpreted in relation to the predefined technical thresholds established for each energy module and the study hypothesis regarding the superiority of a hybrid renewable solution.

The results are organised in three stages. First, the local solar, wind, and geothermal resources are assessed to determine the feasibility of each technology module under the site's environmental and logistical conditions. Second, the technical performance of the evaluated energy scenarios is analysed, including energy balances, reliability indicators, and the contribution of complementary renewable sources. Finally, a comparative financial assessment is presented, benchmarking the alternative system configurations against the conventional fossil-fuel baseline through capital costs, operating expenditures, net present value, return on investment, and payback performance.

3.1 Site resource assessment

The definitive PVGIS simulation at the calibrated 54° tilt angle yielded a total annual in-plane irradiation of 1,897 kWh/m² and an annual electricity output of 1,660 kWh per installed kWp. The critical design month of December registered 4.52 PSH/day, exceeding the Module A minimum threshold of 2.5 PSH by 80.8%. Module A was therefore formally approved as the primary generation source.

Wind resource analysis revealed a very low annual mean velocity of 1.12 m/s (4.03 km/h), well below the 3.0 m/s continuous generation threshold. Consequently, Module B was rejected as a primary generation source. However, transient gust analysis demonstrated intense seasonal peaks of up to 73.4 km/h (November), with the winter quarter recording persistent gusts between 43.9 and 64.4 km/h. Module B was conditionally approved as an auxiliary transient support asset.

Module C (Geothermal) was definitively rejected on two grounds. First, the highly fractured Mesozoic limestone subsoil of the Prebetic system (Martínez del Olmo, 2021) presented low moisture retention and posed severe mechanical drilling challenges, requiring heavy rotary-percussive rigs that could not transit the narrow, unpaved mountain access roads to the plot. Second, the shallow leptosol soil depth profile (rarely exceeding 0.5 m before striking bedrock) rendered horizontal trench collectors economically unviable.

3.2 Scenario technical performance

Scenario 0 (100% ICE Generator) The Genergy Creta ATS 7.5 kW fossil fuel generator, operating continuously 24 hours/day for 365 days, consumed 22,776 litres of fuel annually (Leroy Merlin, n.d.). The cumulative 10-year expenditure reached €433,570, establishing the financial baseline.

Scenario 1 (100% Solar PV – 10 Panels, 8 Batteries) Preliminary analytical sizing yielded a target of 3.41 kWp and 35.09 kWh. Commercial hardware selection (JA Solar 535W TOPCon and Pylontech US5000 modules (Autosolar, n.d. f, b)) required rounding to 7 panels, which was subsequently scaled up to 10 panels (5.35 kWp) and 8 batteries (38.4 kWh) to eliminate a December localised failure rate of 10.2%. The definitive PVGIS simulation confirmed a global annual empty-battery probability of 0.58%, with December reduced to 0.5%. The monthly energy balance recorded a surplus for 11 of 12 months, with the only deficit in January (−51.20 Wh/day, representing less than 0.6% of daily demand).

Scenario 2 (Hybrid Solar-Wind – 8 Panels, 6 Batteries, 1 VAWT) The photovoltaic array was strategically downsized to 8 panels (4.28 kWp) and the battery bank to 6 units (28.8 kWh), with the TESUP Atlas 10 kW VAWT (TESUP, n.d.) integrated to compensate for winter deficits. The pre-wind solar-only simulation identified energy shortfalls in January



(−207.60 Wh/day), March (−69.50 Wh/day), November (−150.60 Wh/day), and December (−143.60 Wh/day). Dynamic analysis of a single hour of transient gust exploitation showed that even brief wind events during these months yielded sufficient energy to eliminate all deficits: November (850 Wh from a 73.4 km/h gust), December (220 Wh from 43.9 km/h), January (580 Wh from 60.5 km/h), March (610 Wh from 62.3 km/h). The final hybrid monthly balance demonstrated positive net generation for all 12 months (*Figure 4*).

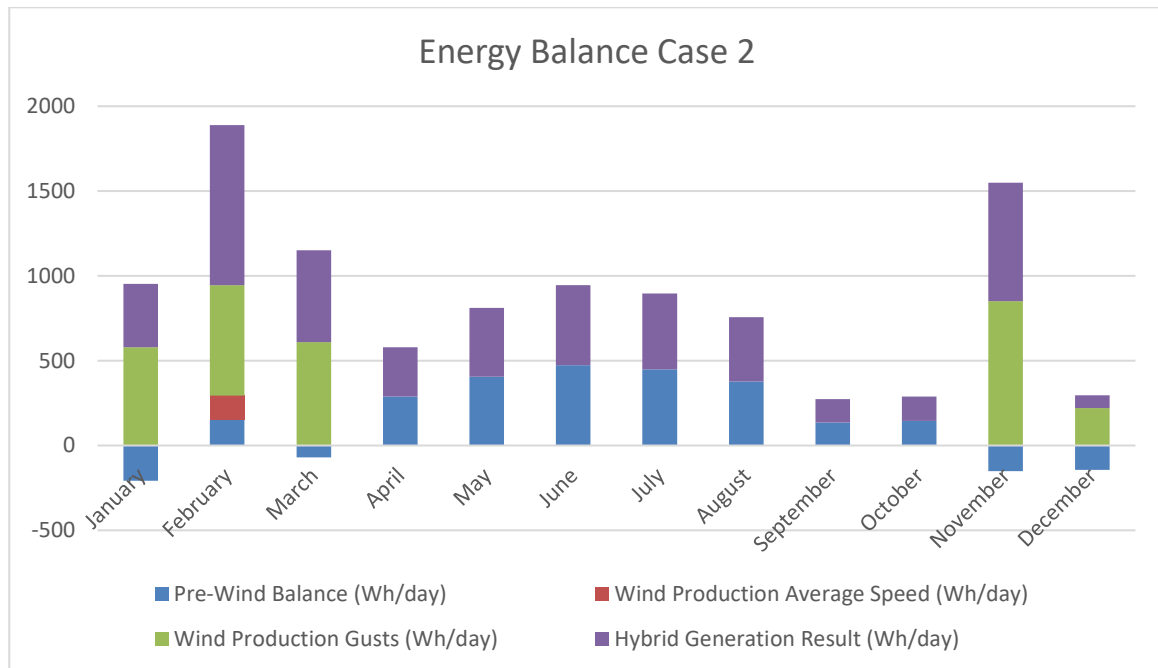


Figure 4. Post-wind energy balance.

The same downsized solar architecture was maintained, replacing the VAWT with the fossil-fuel generator. The generator operated exclusively on days of battery depletion, totalling approximately 10.6 days/year (conservatively rounded to 11), and consumed 686.4 litres of fuel annually – a 97% reduction compared with Scenario 0. However, the OPEX remained penalised by recurrent fuel costs escalating at 4% annually, and a combined maintenance bill of €870/year.

3.3 Financial comparative analysis

Table 1 summarises the financial metrics computed for each renewable scenario against the fossil-fuel baseline at a 5% discount rate over 10 years.

Table 1. Financial metrics comparison for all energy supply scenarios.

Scenario	CAPEX (€)	OPEX/year (€)	NPV – Net Present Value 10yr (€)	ROI – return on investment
Scenario 0 – 100% ICE Generator	2,221	~36,000+	– (Baseline)	–
Scenario 1 – 100% Solar PV (10P / 8B)	14,095	160.00	315,415	29.64



Scenario 2 – Hybrid Solar-Wind (8P / 6B / VAWT)	12,328	120.00	337,406	34.07
Scenario 3 – Solar PV + ICE Backup (8P / 6B)	13,351	~1,934–2,384	320,932	29.87

Note: P = PV panels; B = Pylontech US5000 batteries; VAWT = Vertical Axis Wind Turbine. Bold row indicates optimal configuration. All NPV calculations use a 5% discount rate over 10 years.

4. Discussion

The results confirm that the hybrid photovoltaic-wind configuration achieves total year-round energy self-sufficiency with the lowest CAPEX (€12,328), the highest NPV (€337,406), and the shortest payback period (0.323 years, approximately 4 months) among all evaluated alternatives. These findings are consistent with the broader literature on hybrid off-grid micro-grids, which identifies complementarity between solar and wind seasonal profiles as the primary driver of storage downsizing and CAPEX reduction.

A particularly significant finding concerns the characterisation of the local wind resource. The initial steady-state assessment – revealing a mean annual velocity of just 1.12 m/s – would conventionally lead to the complete rejection of wind energy as a viable component. However, the transient gust analysis reveals that restricting the evaluation to continuous averages introduces a systematic assessment error in turbulent mountain environments. The localised winter gusts, reaching 73.4 km/h, are precisely temporally aligned with periods of solar generation deficit, making even brief exploitation events sufficient to resolve multi-day energy shortfalls. This suggests that in mountainous off-grid contexts, conventional wind feasibility thresholds designed for uniform laminar flow conditions may underestimate the available resource. Future research using higher-frequency anemometric logging (sub-hourly) and VAWT dynamic power-curve modelling could more accurately quantify the energy harvested from transient events.

The rejection of geothermal exploitation (Module C) deserves further contextualisation. The site presented technically adequate subsoil thermal conditions ($T_g \approx 16^\circ\text{C} \pm 1^\circ\text{C}$ at shallow depth), theoretically capable of supporting a Ground-Source Heat Pump. However, the physical constraints – consolidated fractured limestone requiring diamond-tipped percussion drilling and the impossibility of transiting heavy machinery via the mountain access roads – rendered both vertical and horizontal configurations economically unviable. This finding highlights an often-overlooked constraint in off-grid geothermal studies: the logistical accessibility threshold may be a more binding constraint than the geological or thermal one, particularly in remote terrain.

The comparison between Scenarios 1 and 2 reveals the cost efficiency of strategic storage downsizing enabled by wind hybridisation. Scenario 1 required two additional battery units (38.4 vs 28.8 kWh) and two additional PV panels (5.35 vs 4.28 kWp) solely to address the January deficit, adding approximately €1,767 in CAPEX and eliminating the need for wind integration. Scenario 2 achieves a superior financial outcome by investing €1,198 in the VAWT, thereby resolving multiple winter deficit months simultaneously. This demonstrates that in systems with highly seasonal complementarity, infrastructure diversification represents a more capital-efficient strategy than component over-dimensioning.

Scenario 3 illustrates that introducing even minimal residual fossil-fuel dependency substantially erodes the long-term financial performance. Despite operating the generator for only 11 days per year, the 4% annual fuel cost escalation and mandatory maintenance create a compounding OPEX drain, reducing the 10-year NPV to €320,932 – €16,474 below Scenario 2. This differential will continue to widen as carbon pricing mechanisms under the European Green Deal progressively increase fuel costs (Abasova, Zaidi, & Ashraf, 2026).

Several limitations of this study must be acknowledged. First, the wind energy yield from transient gusts is estimated using a static power curve approach applied to recorded peak values, which provides a conservative lower bound but does not capture the full temporal distribution of sub-peak gust events throughout each day. A continuous power integration using high-resolution meteorological time series would improve accuracy. Second, the PVGIS-SARAH3 climate database (EC–



JRC, n.d.) exhibits inherent year-to-year variability (standard deviations of 6.5-25.7 kWh/month), which was accounted for in the Worst Month design criterion but not propagated through a probabilistic reliability analysis. Third, the financial model does not include the potential residual value of components at the end of the 10-year evaluation horizon, nor does it account for battery replacement cycles beyond 10 years, which could alter the absolute NPV values while preserving the relative ranking of scenarios (for instance, for Scenario 2, please see Figure 5):

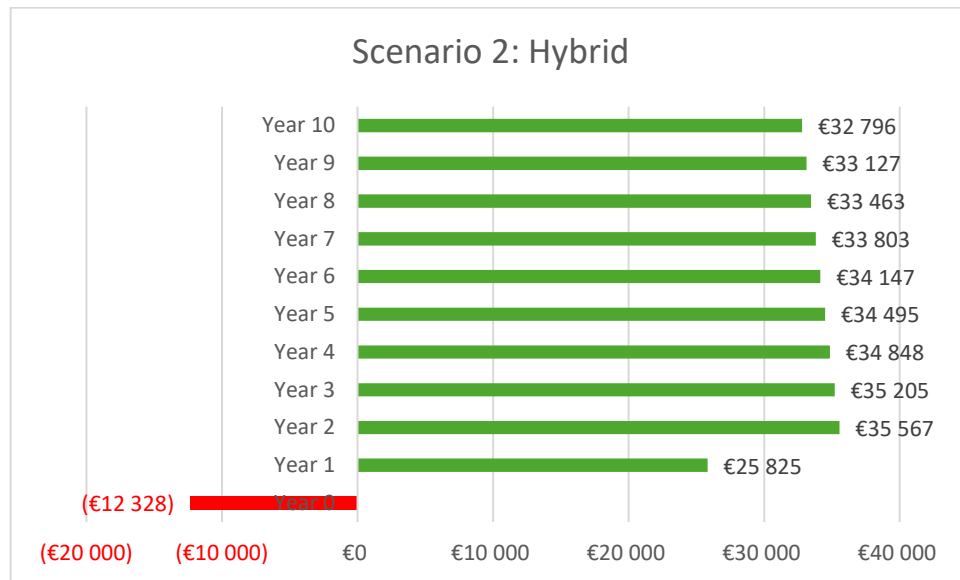


Figure 5. 10-year discounted savings and financial metrics - Scenario 2

5. Conclusions

This study successfully developed and validated a replicable modular engineering framework for the design, resource filtering, and financial benchmarking of off-grid hybrid renewable energy systems in isolated rural Mediterranean environments. Applied to a permanent residential property in El Pla de La Llacuna (Villalonga, Valencia, Spain), the methodology demonstrated the following.

- (1) A hybrid solar-wind architecture (8×535 Wp PV + 28.8 kWh LiFePO₄ + 10 kW VAWT) achieves complete annual self-sufficiency with the most competitive technical and financial performance: CAPEX of €12,328, OPEX of €120/year, NPV – Net Present Value of €337,406, ROI – Return On Investment of 34.07, and a payback period of 0.323 years.
- (2) The modular filtering process formally rejected geothermal exploitation due to logistical inaccessibility and geological drilling constraints. It rejected continuous wind generation due to sub-threshold mean velocities, while approving it as a transient support asset based on intense seasonal gust activity.
- (3) The 100% fossil-fuel baseline accumulated €433,570 over 10 years, demonstrating the economic infeasibility of continued fossil fuel dependence in the context of rising fuel costs and carbon pricing.

The modular catalogue framework constitutes a transferable blueprint applicable to other isolated rural dwellings across Mediterranean mountainous regions. Three primary avenues for future research are identified: (i) continuous empirical data logging of the physical installation to validate and refine the computational sizing coefficients; (ii) evaluation of the additional capacity requirements arising from Electric Vehicle integration as rural electrification shifts toward e-mobility; and (iii) extension of the single-household methodology to Renewable Energy Community (REC) scale, assessing the technical and economic feasibility of interconnecting multiple off-grid properties across the La Llacuna plateau into a shared decentralised smart micro-grid.



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