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A Hybrid Solar–Wind Renewable Energy System With MPPT

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Abstract

Solar and wind generation are each constrained by the intermittency of their primary resource: photovoltaic output falls to zero at night and is depressed by cloud cover, while wind output varies with atmospheric conditions and is strongly site-dependent. Deployed independently, both therefore require either oversizing or substantial storage to meet a firm load. A hybrid renewable energy system (HRES) exploits the partial complementarity of the two resources, so that a shortfall in one may be offset by the other and the storage requirement is correspondingly reduced. This paper presents the architecture, simulation and prototype realisation of a hybrid solar–wind system. The existing single-source arrangement is first characterised: a wind chain comprising turbine, permanent-magnet synchronous generator, three-phase rectifier, boost converter and SPWM-controlled inverter with output filter, and a photovoltaic chain comprising array, boost converter and charge controller under PWM control. The proposed system combines both chains behind a common DC bus with maximum power point tracking, battery storage and a smart inverter interface. A MATLAB/Simulink model incorporating a utility point of connection, a solar array, a diesel generator, energy storage and a variable load was constructed, and its waveform outputs are reported. A laboratory prototype comprising a photovoltaic panel, a small wind turbine and the associated conversion electronics was assembled and operated. The results presented are qualitative and waveform-level: no numerical energy yield, efficiency figure or availability statistic was measured, and consequently none is reported. The limitations of the present evaluation and the measurements required to make it quantitative are stated explicitly.

Introduction

Global energy demand continues to rise with population growth, industrial expansion and technological development, while climate change, air pollution and the depletion of fossil resources make the transition to cleaner supply increasingly urgent. Renewable integration has consequently become a central strategy for long-term sustainability and energy independence.

Hybrid renewable energy systems (HRES) offer a practical route to that integration. By combining two or more renewable technologies — typically solar photovoltaic and wind, with optional biomass, small hydro, battery storage or a backup generator — an HRES exploits the complementary availability of different resources. The result is improved reliability, better operational efficiency and greater energy security than any single source can provide alone, particularly in remote or off-grid locations where conventional grid access is limited or unavailable.

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Figure 1: Emissions from conventional fossil-fuelled generation, the environmental driver for renewable integration.

1. Objectives

- To promote sustainable energy supply and reduce dependence on fossil fuels by harnessing solar and wind resources.
- To reduce greenhouse gas emissions by displacing conventional generation.
- To improve energy security and self-sufficiency through use of locally available resources.
- To provide reliable power to remote and underserved areas through decentralised and off-grid configurations.
- To enhance system performance by optimising the design, integration and control of the conversion chain.
- To support the adoption of advanced technologies including smart grids, energy storage and intelligent control.

2. Contributions

1. Characterisation of the existing single-source solar and wind conversion chains and an explicit statement of the drawbacks that motivate hybridisation.
2. An HRES architecture combining both chains behind a common DC bus with MPPT, storage and a smart inverter interface.
3. A MATLAB/Simulink model of the hybrid arrangement with reported waveform outputs.
4. A laboratory prototype realisation, together with an explicit account of what the present evaluation does and does not establish.

Related Work

Table I summarises the studies reviewed during this work. Three themes recur: the sizing and optimisation of hybrid configurations, the control strategies used to manage power flow between sources, and the role of storage in absorbing the residual intermittency that hybridisation alone does not remove.

Table 1. Reviewed Work on Hybrid Renewable Energy Systems

Author (year)	Contribution
M. A. Mohamed et al. (2023)	Modelling of hybrid renewable systems; examines architectures for varied applications and applies optimisation to improve performance and reduce cost, supported by case studies.
Keyu Jia et al. (2023)	Large-scale hybrid system combining renewables with gas turbines and hydrogen or electrochemical storage; universal modelling and optimisation framework balancing cost against emissions over the life cycle.
Djilali A. B. et al. (2024)	Energy management with improved Perturb and Observe control and battery storage, improving response to dynamic changes in production and demand.
Ibrahim A. W. et al. (2024)	Fast DC-link voltage control using ADRC with hybrid particle swarm optimisation for PV/wind systems; improves voltage regulation under disturbance.
A. Naderipour et al. (2020)	Cost-effective HRES integrating PV, wind, tidal and fuel cell with hydrogen storage; minimises net present cost subject to load deficit probability.

A. Naderipour et al. (2021)	Stand-alone PV–wind–battery system sized by an Improved Grasshopper Optimization Algorithm with a load-following strategy, using real irradiance, wind speed, temperature and demand data.
Patel S. et al. (2023)	Optimal power-flow control for hybrid microgrids with PV, wind and battery, evaluated on a real-time digital simulator platform.
Zaid Bin Siddique et al. (2016)	Stand-alone generation for off-grid areas combining solar and wind with battery, fuel cell and diesel backup managed by power conditioning units.
Kiehbadroudinezhad et al. (2022)	Review of energy storage for renewables covering battery types, economic feasibility and reliability metrics, and optimisation by AI and HOMER.
R. Banik et al. (2020)	Integration of solar, wind and hydro; addresses intermittency through configuration choice, performance metrics and reliability assessment.
Avid et al. (2018)	Review of optimal HRES sizing across traditional, AI-based and hybrid methods, and the role of software tools such as HOMER.
Ramasamy K. et al. (2024)	Power control of hybrid solar–wind systems using a bidirectional converter with advanced MPPT for storage and power-flow management.
Moussa O. et al. (2025)	Hybrid type-2 fuzzy backstepping control for doubly fed induction generators, giving improved stability and faster response under variable wind.
Rajan C. C. A. et al. (2024)	Optimised PV–wind system supporting EV charging stations, with energy management balancing generation, storage and vehicle load.
R. Luna Rubio et al. (2012)	Classification of sizing approaches into traditional analytical and probabilistic methods and AI-based algorithms such as genetic algorithms and particle swarm optimisation.
S. Bentouba et al. (2016)	HOMER-based assessment concluding that wind, PV and a diesel backup can fully satisfy a town’s electricity demand.
J. Bernal-Agustín et al. (2009)	Simulation and optimisation of stand-alone hybrid systems, focusing on PV–wind–battery configurations and cost minimisation under non-linear constraints.

The reviewed work establishes that hybridisation and MPPT are the accepted means of addressing intermittency, and that storage sizing dominates the resulting economics. The present work applies this architecture at laboratory scale and reports what such an implementation demonstrates.

Existing Single-Source Systems

Solar and wind systems are considered first in isolation, since their individual behaviour determines what hybridisation must correct. The existing arrangement is shown in Fig. 2.

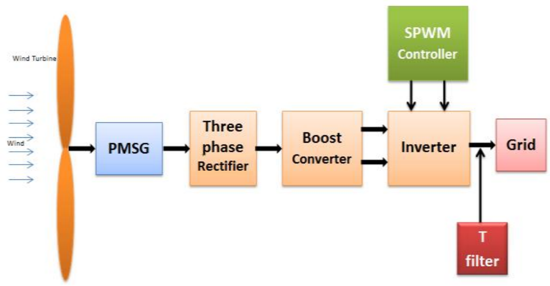

Figure 2: Block diagram of the existing single-source wind conversion chain: turbine, PMSG, three-phase rectifier, boost converter and SPWM-controlled inverter with output filter feeding the grid.

1. Wind Generation

A wind turbine converts the kinetic energy of moving air into mechanical energy and then into electrical energy. As wind crosses the blades, their aerodynamic profile creates a pressure difference between the upper and lower surfaces; the resulting lift turns the rotor about its hub. The rotor drives a shaft, and in most commercial machines a gearbox steps the rotor speed of typically 10–60 rev/min up to the 1000–1800 rev/min required by the generator. Electromagnetic induction within the generator converts the mechanical input to alternating current, which is passed through a transformer to match transmission requirements, with power-conditioning equipment managing voltage, frequency and phase for grid connection.

Modern turbines incorporate yaw mechanisms that rotate the nacelle so the blades face into the wind, pitch control that adjusts blade angle to regulate rotational speed and output, and mechanical and aerodynamic braking that protects the machine in extreme winds. Horizontal-axis machines predominate; vertical-axis designs accept wind from any direction and suit urban or low-wind sites at lower efficiency. Output depends on wind speed, air density, rotor diameter and hub height, and tall towers are used because wind speed increases with elevation.

2. Solar Generation and the PV Array

A photovoltaic array comprises multiple modules of semiconductor cells, typically crystalline silicon, connected in series and parallel to reach the required voltage and current. Each cell generates direct current through the photovoltaic effect when illuminated. Because appliances and grids operate on alternating current, an inverter converts the array output; modern inverters additionally perform maximum power point tracking to optimise harvest and synchronise with grid voltage and frequency.

Modules are mounted on fixed structures angled for the site latitude, or on single- or dual-axis trackers that follow the sun and increase capture at greater cost and complexity. In off-grid systems, surplus energy is stored in batteries for use at night or under cloud; in grid-connected systems it may be exported. Charge controllers prevent overcharge and deep discharge in battery-based installations, and monitoring systems report production and detect faults. Array performance depends on irradiance, orientation and tilt, temperature, shading and soiling, over a typical service life of 25 to 30 years.

3. Drawbacks of the Existing Arrangement

1. Intermittency and variability-Photovoltaic generation is confined to daylight hours and is reduced by cloud and season. Wind generation depends on prevailing conditions and may fall to negligible output for extended periods, particularly at sites with weak wind resource.
2. Storage requirement-Both technologies require storage to bridge periods of low generation. Batteries are costly, limited in capacity and finite in life, so large-scale storage adds materially to installed cost and imposes periodic replacement.
3. Land and space-Both require significant area at scale. Photovoltaic farms occupy large tracts that may displace agricultural or natural land, and are constrained in dense urban settings. Wind installations require open space and are frequently sited in remote or coastal areas, raising transport and installation cost.
4. Environmental and visual impact-Turbine blades pose a risk to birds and bats, and turbines are considered visually intrusive in some landscapes. Large photovoltaic farms can disturb local habitat, and module manufacture and disposal involve materials of environmental concern.

Figure 3: Laboratory kit comprising the small wind turbine and photovoltaic panel used in the experimental arrangement.

Proposed Hybrid System

The proposed system combines solar photovoltaic and wind generation behind a common DC bus, with energy storage and intelligent control. Solar output is available during daylight while wind may generate at any hour, so the two partially offset one another; biomass or micro-hydro may be added as steady backup where the resource exists.

Generated energy is routed to a centralised energy-management stage that monitors environmental conditions, consumption and production, and allocates power between immediate load, storage and export. Surplus beyond immediate consumption is stored in batteries, which buffer periods of low generation; alternatively surplus may drive an electrolyser to produce hydrogen for later reconversion through a fuel cell. Before delivery, smart inverters convert the DC from generation and storage to alternating current and regulate voltage and frequency. Where a grid interface is present, bidirectional flow permits both import and export, supporting net metering and demand-side management. IoT-based monitoring provides performance tracking, predictive maintenance and remote diagnostics.

1. Photovoltaic Stage

Conventional silicon modules have approached their practical efficiency ceiling of approximately 26 %. Perovskite–silicon tandem cells address this limit by depositing a perovskite layer above the silicon cell: the perovskite absorbs the short-wavelength portion of the spectrum while the silicon absorbs the longer wavelengths, so the tandem converts more of the incident spectrum than either material alone. Certified tandem efficiencies exceeding 33 % have been demonstrated. Perovskites can be processed at low temperature and printed by roll-to-roll methods, offering potential cost reduction, and continuing work addresses their stability against moisture and ultraviolet degradation.

2. Wind Stage

Turbine capacity has grown substantially, with offshore machines now specified at rotor diameters exceeding 310 m and carbon-fibre blades, rated for mean wind speeds of 8.5–10 m/s and for typhoon survival in both fixed-bottom and floating configurations.

Floating turbines extend wind development into deep water where fixed foundations are impractical, typically beyond 60 m depth. The machine is mounted on a buoyant platform — semi-submersible, spar-buoy or tension-leg — moored to the seabed, allowing operation in water over 100 m deep. Floating installations access stronger and steadier winds, disturb the seabed less than fixed foundations, and can be assembled onshore and towed to site, reducing offshore construction. The Kincardine floating wind farm off Aberdeen, operational since 2021, comprises six turbines of nearly 50 MW combined capacity on semi-submersible platforms moored in 60–80 m of water, demonstrating commercial-scale deployment.

3. DC–DC Conversion

A DC–DC converter transforms one direct voltage to another, stepping it up, stepping it down or inverting polarity. Such converters are essential wherever generation voltage does not match the storage or bus voltage. Operation relies on switching devices such as MOSFETs or IGBTs together with inductors, capacitors and control circuitry, which regulate energy transfer through high-speed switching cycles. Four topologies are relevant: the buck converter, which steps voltage down; the boost converter, which steps it up; the Cuk and SEPIC converters; and the buck–boost converter, which performs either function as required. The photovoltaic conversion chain with its boost stage, charge controller and PWM control is shown in Fig. 4.

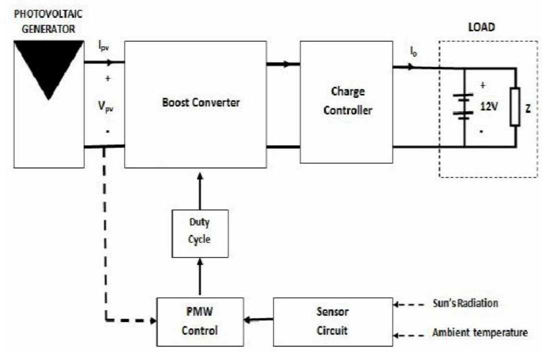

Figure. 4: Photovoltaic generation chain with boost converter, charge controller and PWM control referencing solar irradiation and ambient temperature.

4. Rectification

Rectification converts alternating current to direct current and is required wherever the wind generator output must feed a DC bus. The basic element is the diode, which conducts in one direction and blocks the other. A half-wave rectifier conducts during one half-cycle only, producing a heavily rippled output and wasting half the input; it is simple but inefficient. A full-wave rectifier uses both half-cycles, either through two diodes with a centre-tapped transformer or four diodes in a bridge arrangement, giving a smoother output and higher average voltage.

The bridge rectifier, shown in Fig. 5, is the most widely used full-wave form because it removes the need for a centre-tapped transformer, simplifying the design and reducing cost. Four diodes are arranged so that output current flows in the same direction irrespective of input polarity. Residual ripple is filtered by capacitors or inductors. Schottky or fast-recovery diodes reduce forward loss in high-efficiency applications, while silicon-controlled rectifiers and triacs provide controlled rectification where variable DC output is required. Wide-bandgap devices in silicon carbide or gallium nitride permit faster switching, higher efficiency and reduced heat generation in compact designs.

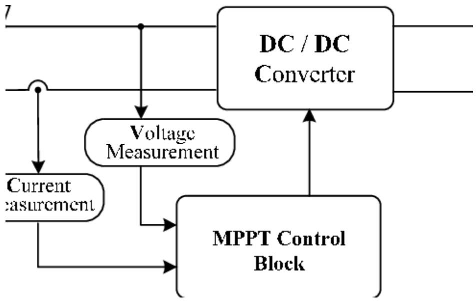

Figure. 5: Bridge rectifier configuration used in the conversion chain.

5. Maximum Power Point Tracking

Photovoltaic arrays exhibit a non-linear power–voltage characteristic, so the power delivered varies with irradiance, temperature and load. A maximum power point tracking (MPPT) controller continuously adjusts the operating point to coincide with the maximum power point, at which the array delivers the greatest available power. Without tracking, the system would operate away from this point and harvest correspondingly less energy.

MPPT controllers implement algorithms such as Perturb and Observe, Incremental Conductance and Constant Voltage, adjusting the duty cycle of a DC–DC converter to boost or buck the array voltage so that it matches the battery or grid voltage. Reported efficiency improvements reach up to 30 % relative to systems without tracking, particularly where sunlight is intermittent or variable. The technique is not confined to photovoltaics: it applies equally to wind turbines and fuel cells, where output voltage likewise varies with conditions. In off-grid installations MPPT is generally integrated into the charge controller, and in grid-tied systems into the inverter. Beyond energy capture, the controller also protects the installation by preventing battery overcharge. The MPPT control arrangement is shown in Fig. 6.

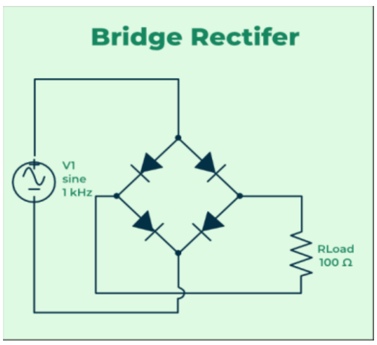

Figure 6: MPPT control arrangement with voltage and current measurement driving the DC–DC converter duty cycle.

Simulation and Prototype Results

1. Prototype Realisation

The hardware realisation is shown in Fig. 7. It comprises the photovoltaic panel, the conversion and control board carrying the rectification, converter and switching stages, and the associated wiring to the storage and load. The system was assembled and operated in the laboratory.

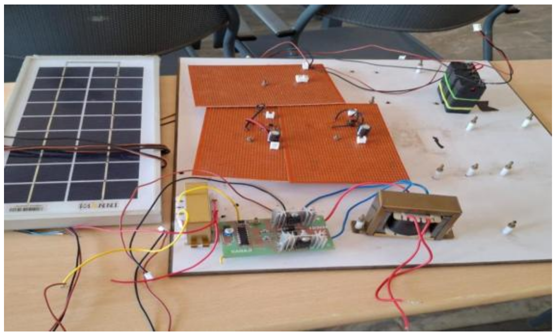

Figure 7: Hardware realisation of the hybrid system showing the photovoltaic panel and the conversion and control board.

2. Simulation Model

A MATLAB/Simulink model of the hybrid arrangement was constructed and is shown in Fig. 8. The model incorporates a utility point of connection with an islanding command, a solar array, a diesel generator, an energy-storage element and a variable load, together with the measurement blocks used to observe bus behaviour.

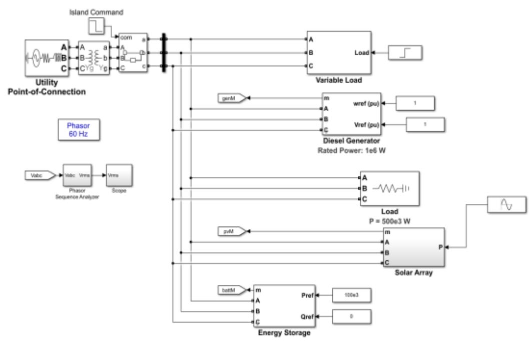

Figure 8: MATLAB/Simulink model of the hybrid system incorporating the utility point of connection, solar array, diesel generator, energy storage and variable load.

3. Waveform Outputs

The simulated waveform outputs are reproduced in Figs. 9 to 11. Fig. 9 shows the switching-level output of the converter stage; Fig. 10 shows the settling behaviour of the regulated quantity following the initial transient; and Fig. 11 shows the steady-state periodic output of the inverter stage together with the associated switching waveform.

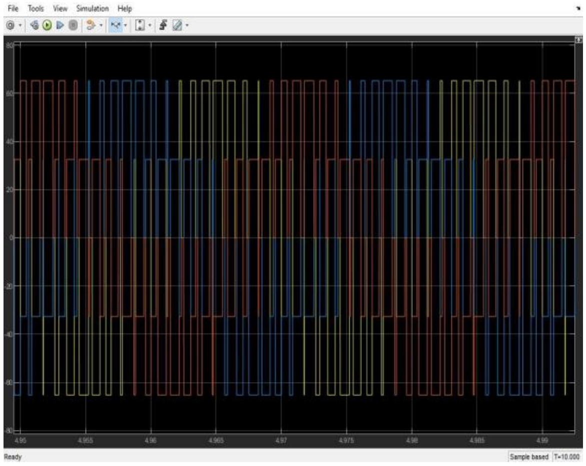

Figure 9: Simulated switching-level output of the converter stage.

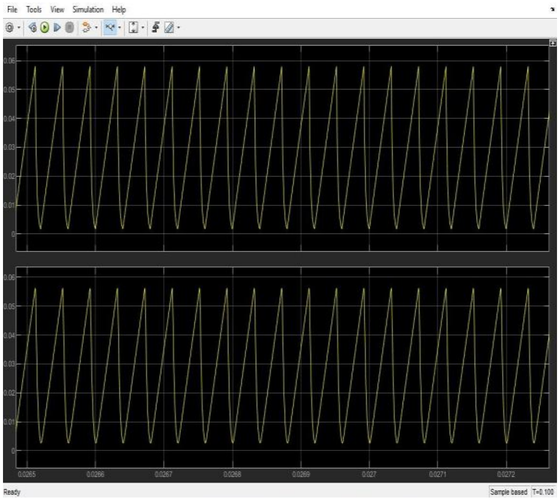

Figure 10: Simulated response showing the initial transient and subsequent settling of the regulated quantity.

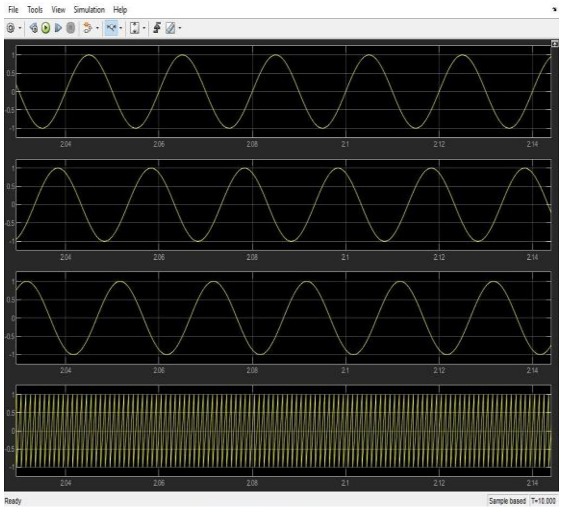

Figure 11: Simulated steady-state periodic output of the inverter stage with the associated switching waveform.

4. Nature of the Results Reported

The scope of these results requires a precise statement. The simulation confirms that the modelled arrangement produces stable periodic output and that the regulated quantity settles following the initial transient, which establishes that the control structure is self-consistent. The prototype confirms that the physical conversion chain can be assembled from the specified components and operated.

Neither result is quantitative. No irradiance, wind speed, generated current or delivered energy was logged during operation; no efficiency was computed for any conversion stage; no comparison was made between the hybrid arrangement and either source acting alone; and no availability or self-sufficiency statistic was derived. Claims that the hybrid system improves reliability, reduces cost or increases captured energy relative to a single-source system are supported by the literature of Section II, not by measurements taken here, and are attributed accordingly throughout this paper.

Discussion

Hybridisation addresses intermittency structurally rather than by oversizing. Where solar output falls with cloud or nightfall, wind may continue; where wind falls calm, solar may be available. The residual mismatch is absorbed by storage, which is why hybrid configurations generally require less storage than a single-source system meeting the same firm load. This is the mechanism the architecture of Section IV is designed to exploit.

The extent of the benefit, however, is site-specific and depends on the degree to which the two resources are genuinely anti-correlated at the location concerned. A site where wind and solar peak together yields far less hybridisation benefit than one where they alternate. Establishing that correlation requires concurrent time-series measurement of both resources at the site over a

representative period, which was not undertaken here. The literature values cited in Section II were obtained at other sites and cannot be transferred to this installation without such measurement.
The practical value of the work is therefore the demonstrated conversion chain and control structure rather than a quantified energy benefit. The architecture is complete from resource to load, the components are specified, the control structure simulates stably and the hardware operates. What remains is measurement.

Limitations

- No environmental or electrical data were logged during prototype operation, so no energy yield, efficiency or capacity factor can be computed.
- The hybrid arrangement was not compared experimentally against solar-only or wind-only operation, so the benefit of hybridisation is not quantified for this installation.
- Simulation results are waveform-level and confirm control stability rather than energy performance; no numerical output is extracted from them.
- Resource complementarity at the installation site was not measured, so the site-specific hybridisation benefit is unknown.
- Storage sizing was not optimised against a measured load profile, and no economic analysis was performed.
- Prototype operation was of short duration; no conclusion regarding long-term reliability or degradation is supported.

The measurements required to close these gaps are: concurrent logging of irradiance and wind speed at the site over a representative period; logging of generated voltage and current at each conversion stage so that stage efficiencies can be computed; a load profile against which storage can be sized; and a comparative trial of hybrid against single-source operation under identical conditions.

Conclusion

A hybrid solar–wind renewable energy system has been specified, simulated and realised in prototype form. The existing single-source arrangements were characterised and their drawbacks identified: intermittency, storage cost, land requirement and environmental impact. The proposed architecture combines both sources behind a common DC bus with maximum power point tracking, battery storage and a smart inverter interface, with provision for grid interconnection and IoT-based monitoring.
A MATLAB/Simulink model incorporating the utility connection, solar array, diesel generator, storage and variable load was constructed and produced stable periodic output with the regulated quantity settling after the initial transient. A laboratory prototype comprising the photovoltaic panel, small wind turbine and conversion electronics was assembled and operated successfully.
These results establish that the architecture is self-consistent in simulation and realisable in hardware. They do not quantify its energy performance: no yield, efficiency, availability or comparative benefit was measured, and none is claimed. The contribution is therefore a complete and specified hybrid conversion chain together with an explicit measurement plan by which its performance could be established.

Future Scope

- Instrumented evaluation-The priority is the measurement programme of Section VII: concurrent resource logging, stage-by-stage electrical measurement, load profiling and a comparative trial against single-source operation.
- Storage and hydrogen-Next-generation storage including solid-state and flow batteries, and green hydrogen produced by electrolysis from surplus generation and reconverted through fuel cells, would extend the buffering horizon from hours to seasons.
- Intelligent energy management-AI-based energy management with predictive load balancing, informed by real-time data analytics, would allow allocation decisions to anticipate rather than follow changes in generation and demand.
- Smart grid integration-Closer integration with smart grid infrastructure would support bidirectional flow, net metering and participation in local energy markets, while IoT-based diagnostics would extend service life and reduce downtime.

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