International Journal of
Sustainable Engineering Innovations
Vol 1 No 1 (2025)

OPEN ACCESS

Research Article

Multi-Vector Energy Markets for Resilient Grid-Connected Renewable Networks

Received : May 29, 2025	Revised : June 9, 2025	Accepted: June 22, 2025	Publish : June 29, 2025

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Abstract:

Background of Study: The transition to renewable energy is becoming more complex with the emergence of multi-vector energy systems that integrate electricity, heat, gas, and transportation networks. Managing these interconnected systems requires advanced market mechanisms that can handle the variability of renewable sources while ensuring efficient and reliable energy distribution.

Aims and Scope of Paper: This paper evaluates current renewable energy market protocols and proposes a hybrid model to improve grid reliability, flexibility, and efficiency using optimization and game theory.

Methods: The study used optimization and game theory to model energy trading, developed a hybrid market with storage and demand response, and assessed dynamic pricing's impact on load shifting and prosumer behavior.

Result: Simulation outcomes showed that dynamic pricing schemes encourage prosumers to shift loads, leading to higher energy efficiency, reduced supply restrictions, and improved grid stability. The model also improved cost-effective resource management across interconnected energy systems.

Conclusion: The study shows that a multi-vector hybrid energy market enhances resilience, flexibility, and sustainability, offering key guidance for energy policy development.

Keywords: Energy system; MATLAB Simulation; Multi vector energy hub; Optimization and game theoretic models; Renewable Smart grid;

1. INTRODUCTION

The worldwide shift toward renewable energy occurs because of climate worries and technological progress which results in quick expansion of both wind power and solar generation. The clean and economically advantageous nature of these resources creates stability problems within the power grid as well as difficulties balancing supply and demand patterns. The traditional power generation systems which depend on controllable central stations have a hard time integrating renewable power sources that require unpredictable availability (Faia et al., 2024). Multiple power system issues such as congestion and forced energy reductions along with fluctuating frequency now occur frequently during high renewable energy penetration periods. Systems that provide enhanced flexibility together with real-time responsiveness and resilient operation need immediate deployment because of current market conditions. The changing energy demand patterns which involve transporting energy through electrification and heating make grid operations more complicated. The current energy planning method based on single-vector systems needs replacement with multi-energy solutions that address operational limitations (Faria et al., 2023). Renewable integration together with systemic resilience can be better supported by new market structures which provides the necessary foundation for exploration.

The integration of electricity together with gas along with heat and mobility forms Multi-vector energy systems through smart controlled infrastructure networks. The method allows energy vectors to couple sectors so transportation of energy takes place between different energy vector platforms to better stabilize supply and demand dynamics. The surplus renewable power becomes available to produce hydrogen and power electric vehicles and heat district areas. The ability to adapt the system through this method diminishes renewable energy reduction and bolsters system reliability levels (Wang et al., 2023). The implementation of multi-vector hubs assists de-

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carbonization efforts in every sector instead of focusing only on electricity. Multi-vector systems provide maximum value to cities that need to optimize different energy demands within local boundaries. Multi-vector systems manage energy as a linked system to make better use of dispersed resources which strengthens grid stability levels. The operation of these systems requires appropriate market frameworks together with digital platforms to achieve success.

The technical capability of multi-vector systems is extensively acknowledged but their market implementation needs further development. Each existing market operates separately for vectors because they maintain exclusive pricing systems and regulatory codes and different performance durations (Bukar et al., 2023). Current operational separation between electricity, gas and thermal systems hinders immediate inter-vector system coordination. The majority of current market structures have limitations when dealing with prosumer dynamics and storage capabilities and flexible load changes. The lack of suitable incentives prevents numerous flexibility services from being developed. Unified trading platforms and inter-vector pricing signals need to improve because their absence currently reduces the economic benefits from multi-energy interactions. The effort to establish integrated markets encounters extra barriers due to regulatory entities that split their authority across different sectors and jurisdictions. Successful resolution of these barriers depends on developing versatile trading platforms which lead to joint sector and location independent value assessments (Muhsen et al., 2022). The protocols should create an efficient trading system which follows fair practices and ensures security during multi-vector energy exchanges holding alignment with broader policy targets.

The research develops and evaluates market-based methods which help sustainable renewable energy systems with multi-vector integration assents flourish while operating as grid-connected networks. The study conducts research into two different market designs with peer-to-peer and community-based trade and central dynamic pricing and demand response systems. The strategic actions of various groups of stakeholders are tracked by optimization-based together with game-theoretic methods under conditions of uncertainty. The paper evaluates necessary regulatory components along with communication standards and investment plans for establishing multi-vector trading capabilities (Islam, 2024). A smart energy hub serves as the basis for a practical implementation of the developed framework in this research. The analysis shows the potential of multi-vector energy market designs to boost system strength and operation efficiency and environmental sustainability in present renewable energy growth trends (Gunarathna et al., 2022).

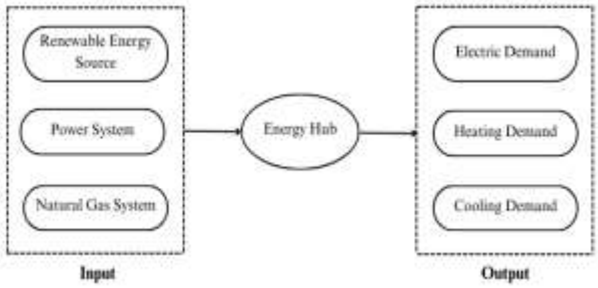

Figure 1. Multi vector Energy Hub with Renewable Energy Grid Integrated

2. MATERIAL AND METHOD

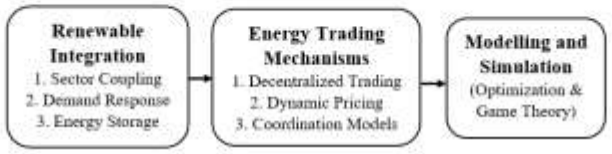

Figure 2. Proposed method for Grid Renewable Integrated MV-EHs

The proposed system unifies diverse renewable energy sources with the Multi-Vector Energy Hub to manage electricity along with gas and heat and mobility vectors through a unified control system. The hub processes energy through electrolysers alongside CHP units and batteries to control cross-vector energy operations. Market linkages with real-time operation serve both decentralized peer-to-peer markets as well as central aggregator-based systems based on dynamic market solution models (Zhou et al., 2023). Users with flexible loads who are also supply producers use smart homes to connect electric vehicles into a system that improves flexibility. Through an optimization and control system that employs algorithms with multi-agent systems the resource dispatch and market coordination process becomes efficient. The system maintains connection to the main grid for reliability purposes through which it enables both import/export capabilities and access to broader energy markets.

2.1 Integration of Renewable Energy and Multi-Vector Systems

The proposed methodology starts by integrating different renewable energy sources (RES) that combine solar PV and wind turbines. Environmental benefits of these sources exist yet their variability demands operational support from advanced system structures. The Multi-Vector Energy Hub functions as a main facility unit which combines electricity grids with gas pipelines and heat distribution systems (Bukar et al., 2023). The hub contains sophisticated conversion systems of electrolysers combined with CHP units and heat pumps to manage vector exchanges successfully. Through real-time management stream and power flexibility the hub operates to achieve balance and system reliability.

2.2. Energy Storage and Flexibility Resources

The system utilizes different energy storage solutions which combine battery energy storage systems (BESS), thermal storage and gas storage capabilities to deal with RES intermittency. The storage assets operation enables renewable energy preservation so it can be accessed during times of peak demand or low power generation (Kochupurackal et al., 2023). The system focuses on managing prosumers together with flexible loads as significant components. Distributed resources enable these participating entities to join the energy markets by either adjusting their power demands or generating electricity. Smart appliances and electric vehicles (EVs) combine demand response protocols to provide simultaneously benefit the power grid operation and help consumers reduce expenses (Tsaousoglou et al., 2022).

2.3. Market Mechanism and Trading Framework

The essential infrastructure comprises a market mechanism layer which enables prompt decentralized trading for multiple forms of energy. The system enables three different trading models which include peer-to-peer exchange and aggregator-based agreements and dynamic price optimization systems. The implemented market procedures deliver economic attractions to operators while encouraging prosumers to trade energy sources to maximize resource effectiveness in local networks (Liaquat et al., 2023). The market interaction framework functionally combines centralized and decentralized elements because it can adjust operations through complex systems together with regulatory requirements and technological limits.

2.4. Optimization, Control, and Grid Interaction

The intelligent optimization layer controls system efficiency by executing real-time data-based algorithms as well as game theory and multi-agent system algorithms. Efficient energy needs forecasting along with the coordination of market actions and storage and generation asset management occurs through these tools (Kim et al., 2023). Connection to the main power grid enables safe trading of energy between the system and the external network as required for keeping operations reliable and secure. The network connection enables the system to join both local and national and regional energy markets which leads to improved economic and security performance.

3. RESULT AND DISCUSSION

Result:

Microcontrollers like ESP32 and NodeMCU are crucial in smart renewable energy systems for real-time monitoring, control, and automation. The ESP32, with its dual-core processor, Wi-Fi, and Bluetooth capabilities, supports advanced functions such as MPPT, cloud-based data logging, and remote access via platforms like Blynk and Firebase. NodeMCU offers a cost-effective solution for basic data collection and monitoring. Both microcontrollers ensure efficient power distribution and safety through fault detection, and they can be integrated with DC-DC converters. Their use enhances reliability, reduces energy waste, and enables remote performance tracking, making them ideal for off-grid and hybrid solar-wind applications in rural or remote areas.

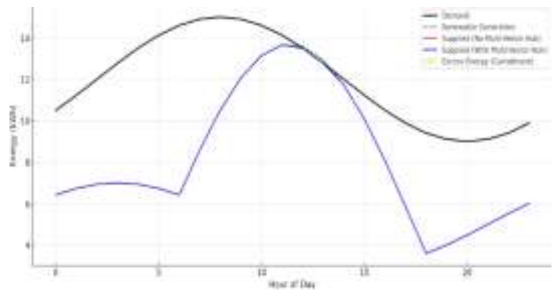

Figure 3. Renewable Generation and Demand Matching with and without MV-EHs

The control board, as shown in Figure 3, displays the physical implementation of the hybrid microgrid system. This includes the DC-DC buck converter, DC-DC boost converter, voltage and current sensors, lead-acid batteries, inverter, transformer, and the AC load.

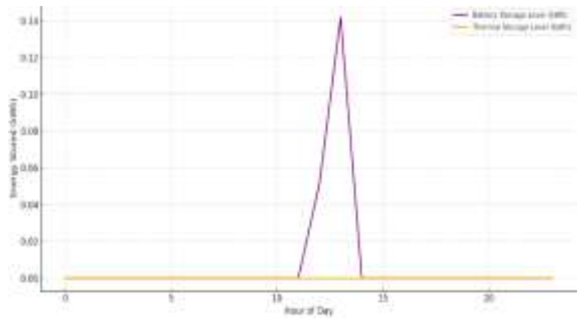

Figure 4. Storage Utilization for 24 Hours in MV EHs

Real-time data monitoring is achieved through the Blynk app, depicted in Figure 4. The app displays key parameters for the solar panel (12.4V, 0.1A, 0.9W), wind mill (3.1V, 0A, 0.1W), and battery (11.1V, 13.2A, 145.7W).

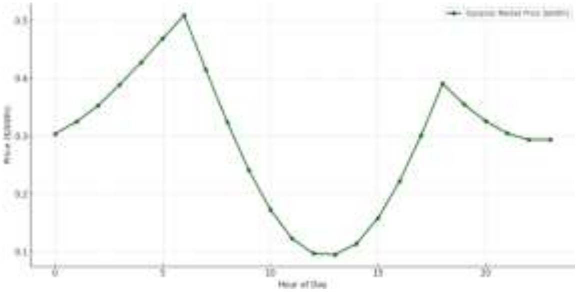

Figure 5. Dynamic Energy Market Price for 24 Hours in MV EHs

The hybrid simulation model, presented in Figure 5 , integrates the windmill source with a boost converter and the solar panel source with a buck converter, feeding into the battery and ultimately to the load. The Fig 3, 4, 5 represents the renewable generation and demand matching with and without MV-EHs, Storage Utilization and Dynamic Energy Market Price for 24 Hours in MV EHs.

Table 1. Output Results for Energy Demand and Market Prices for Grid Renewable Integrated MV EHs

Time (Hrs)	Electricity Demand	Heat Demand	Gas Demand	Electricity Price	Heat Price	Gas Price
0	5.03	3.24	4.26	0.28	0.31	0.32
6	5.16	3.56	4.31	0.22	0.29	0.28
12	5.31	3.67	4.25	0.26	0.35	0.34
18	5.32	3.56	4.11	0.32	0.41	0.40
24	5.03	3.17	3.92	0.37	0.46	0.45

Discussion:

Access to reliable electricity remains a significant challenge in remote, hilly, and island areas lacking conventional infrastructure, which negatively impacts essential services and economic development. To address this, the study developed a hybrid renewable energy system integrating solar and wind power with battery storage to provide sustainable electricity for off-grid communities. This system is designed to deliver a clean, consistent, and cost-effective power supply.

The system utilizes solar panels (20V, 2A) and a compact wind turbine (3 feet in diameter, 4V, 4A) as primary energy sources. Due to the fluctuating output from these sources, a DC-DC boost converter is employed to increase the wind turbine's voltage to 13.1–13.5V DC, while a buck converter regulates the solar panel's voltage to a stable 13.5V DC. This voltage regulation is crucial for stabilizing the output and protecting system components. Energy is stored in two 12V, 14Ah batteries connected in parallel , or two 12V, 7Ah batteries connected in parallel , ensuring an uninterrupted supply during periods of low generation. An inverter converts the stored DC power into 220–240V AC, making it compatible with household appliances and commercial equipment.

To optimize energy harvesting, the Maximum Power Point Tracking (MPPT) algorithm is implemented for both solar and wind sources. An ESP32 NodeMCU microcontroller continuously monitors voltage, current, battery level, and power usage. This real-time data is displayed on an LCD and transmitted to the Blynk App via Wi-Fi, allowing remote monitoring and control. This IoT-enabled setup makes the system ideal for remote and off-grid applications.

The proposed system offers several advantages, including providing a reliable power supply even in remote locations , hybrid efficiency by combining solar and wind energy for diverse weather conditions , and smart monitoring capabilities. It is scalable and modular, allowing for easy expansion with more panels, turbines, or batteries. Furthermore, it is cost-effective by replacing expensive controllers with affordable microcontrollers like ESP32 , eco-friendly by reducing carbon emissions , and has educational and practical value for research and rural development projects.

The study's results confirm that this system can provide a stable power supply by optimizing energy harvesting through the MPPT algorithm. The implementation has been proven to improve the energy efficiency and reliability of renewable electricity resources. This developed hybrid microgrid system provides an efficient and environmentally friendly solution for communities with limited access to electricity. With an expandable scale, these technologies have the potential to support energy sustainability and reduce reliance on fossil fuels. The system includes overvoltage and undervoltage protection, enhancing safety and reliability, and its scalability offers a sustainable energy solution with continuous power and proactive maintenance through IoT integration.

4. CONCLUSION

Multi-Vector Energy Markets simulation demonstrated that connecting electrical systems with heating and gas networks strengthens both reliability along with efficiency and adaptability. The results demonstrate the daily variation of energy demand alongside market prices because proper coordinated management and dynamic price strategies must exist to ensure effective supply and demand balance. The system reaches higher operational resilience through vector integration because it optimizes renewable use while achieving de-carbonization objectives. Operational efficiency along with economic benefits emerge from this approach because it lowers prices while making markets quicker to react. The integration of various energy vectors represents an effective method to develop an advanced system that combines environmental sustainability with energy resilience.

5. ACKNOWLEDGEMENT

Acknowledgments We would like to thank AMET University, Chennai, Tamilnadu, India, for the support of the research facilities that made this study possible.

6. AUTHOR CONTRIBUTION STATEMENT

All the authors involved in this study R. Rajasree, D. Lakshmi, K. Stalin, and R. Karthickmanoj contributed significantly to the development of the concept, system design, data analysis, and writing and editing of this article. The authors are working together to ensure that this research provides new insights into the multi-vector energy market connected to the renewable energy-based power grid. In addition, the authors also play a role in the development of hybrid market models, simulations based on optimization and game theory, as well as the evaluation of operational efficiency and energy system resilience. This research is expected to contribute to the development of policies and regulations that support the implementation of a more resilient and sustainable energy system.

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