ISSN: 2093-5374 / E-ISSN: 2093-5382

Hybrid NSGA-III and Genetic Programming (GP) Integrated with Game Theory for Energy Trading and System Optimization

Minu Mary Joy[1*], and Dr.H. Vennila[2]

[1*]Research Scholar, Department of Electrical and Electronics Engineering, Noorul Islam Centre for Higher Education, Kumarakoil, Tamil Nadu, India. minujoy3@gmail.com, https://orcid.org/0009-0003-5403-1064

[2]Associate Professor, Department of Electrical and Electronics Engineering, Noorul Islam Centre for Higher Education, Kumarakoil, Tamil Nadu, India. vennilarajesh@yahoo.co.in, https://orcid.org/0000-0001-6516-3124

Received: February 02, 2026; Revised: March 09, 2026; Accepted: April 27, 2026; Published: June 30, 2026

Abstract

Hybrid Renewable Energy Systems (HRES) have become an important pathway for developing sustainable means of electricity generation using renewable energy technologies and storage. This occurs while responding to multiple and conflicting objectives, including cost minimizing, reliability maximization, minimizing losses and meeting environmental sustainability. The complexity of incorporating a variety of HRES constraints is compounded through also needing to participate in energy trading between micro grids, HRES units and utility grids, that are reliant on unpredictable markets and demand-supply uncertainty. To study how to deal with progressed modelling uncertainty, to propose a new method for the optimization of sustainability frameworks, through Hybrid NSGA-III, Generation Programming, and Game Theory. Hybrid NSGA-III ensures the multi-objective optimization of system sizing and operations, Generation Programming allows for evolving simulation of the uncertainty in the operating system solutions, and game theory approaches provides fair and efficient energy trading. A full statistical comparison with benchmarks (NSGA-II and MOEA/D) has shown that the suggested framework is the best. Specifically, the proposed framework showed a 11% ± 2.3 cost reduction and 9% ± 1.8 emissions reduction in 2 for 1 trading efficiency increase, 9-10% in reliability improvements compared to benchmarks, and developed a diverse Pareto front has shown and illustrated (helps to develop manage the trade-off between conflicting objectives). Applying an analysis of variance (ANOVA) and 95% confidence interval also indicators that the proposed approach improves robustness and represents statistically significant improvements throughout the presented development efforts. Overall, the proposed integration provides a scalable, resilient, and intelligent optimization of Hybrid Renewable Energy Systems (HRES), and contributes to the conversational development toward more sustainable and economically viable decentralized energy markets.

Keywords: Hybrid Renewable Energy Systems (HRES), Multi-objective Optimization, Hybrid NSGA-III, Genetic Programming (GP), Game Theory, Energy Trading, Energy Storage, Market Dynamics, System Optimization, Sustainability.

Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications (JoWUA), volume: 17, number: 2 (June-2026), pp. 1-19. DOI: *10.58346/JOWUA.2026.I2.001*

*Corresponding author: Research Scholar, Department of Electrical and Electronics Engineering, Noorul Islam Centre for Higher Education, Kumarakoil, Tamil Nadu, India.

1 Introduction

In today's world, growing global energy demand combined with the pressing need to cut back greenhouse gas emissions has led to the proliferation of Hybrid Renewable Energy Systems (HRES). HRES are hybrid energy systems that integrate renewable energy systems (solar, wind, biomass) with energy storage to create a sustainable and reliable energy supply (Vakhguelt & Jianzhong, 2023; Kapoor & Iyer, 2024). HRES, like all renewable systems, present many advantages over traditional fossil-fuel-based systems in terms of environmental factors and energy diversification, and are critical in helping our society transition to net-zero energy systems (Ajiboye et al., 2023; Jain & Babu, 2024; Premkumar & Shanmugasundaram, 2019). Even though HRES provide new potential solutions to energy supply solutions, their design and operation are extremely complex due to the intermittent nature of renewable energy, variability of energy demand, and uncertainty of market prices. Finding a low-cost, reliable system with a minimal environmental footprint is a very complicated multi-objective problem. In addition, energy trading between the local microgrids, HRES units, and utility main grid creates another layer of complexity that must be managed using advanced optimization findings (Huang et al., 2024; Anaya Menon & Srinivas, 2023).

As a result of the complexity of HRES optimization, meta-heuristic algorithms have proven considerably useful for optimizing non-linear multi-objective optimization problems (Tomar & Vyas, 2022). Hybrid optimization approaches offer superior performance compared with a forces algorithm and can provide more diversity of solutions, faster convergence, and better uncertainty mitigation. These types of methods have already been reported to optimize energy storage, scheduling, and manage load in HRES (Taghizad-Tavana et al., 2025; Abulail, 2025). Out of the multi-objective evolutionary algorithms available, NSGA-III non-dominated sorting genetic algorithm (NSGA-III) has been shown to be the most competent algorithm for solving high-dimensional optimization problems (Dubois, 2023). In contrast to older algorithm designs like NSGA-II, NSGA-III used reference points with advanced diversity preservation strategies to achieve coherent and consistent solutions through accurate Pareto fronts (Mohammed et al., 2024). The literature shows the application of NSGA's performance in virtually all aspects of HRES optimization including total dynamics optimization of system cost min, improving reliability of energy, and minimizing emissions. Accordingly, it's use in handling very complex energy systems makes it indispensable (Salami et al., 2025; Yang & Li, 2024).

Besides evolutionary algorithms, GP offers the ability to adaptively model and make decisions in dynamic environments. GP is particularly useful because it is capable of evolving analytical expressions as well as strategies for energy management with uncertainty in renewable generation and demand. Furthermore, by utilizing GP with NSGA-III, the optimization framework is more adaptive and allows the system to learn decision rules and adapt trading strategies independently to improve resource allocation (Zhang et al., 2003). Game theory provides frameworks for modeling strategic interaction amongst prosumers, microgrids, and utilities operating in decentralized energy markets (Wang et al., 2014). It provides both cooperative and non-cooperative game-theoretic frames which can be leveraged when framing fair pricing strategies, demand response strategies, and equilibria in energy markets to provide stability in these decentralized markets. Therefore, if game theory can be used as part of the HRES optimization problem, stable economic trade based on sustainability will help ensure both sustainability and profit in uncertain relying energy trading conditions (Tushar et al., 2020).

While meta-heuristics, game theory, and GP have all advanced areas of energy optimization for HRES individually, there are only a few examples of integrated approaches that make use of HRES optimization with meta-heuristics, GP, and game theory. Additionally, most research that exists in this area largely focuses on either system design optimization of a HRES, or energy trading strategies and does not focus on optimizing the two simultaneously. This research provides a new, unique hybrid scenario to converged NSGA-III, GP, and game theory into same framework to simultaneously optimize the multi-objective optimization design and trading strategies in HRES (Duan et al., 2025).

Key Contributions of the Research

This research is unique in its complex development of a cohesive optimization and trading framework that merges Hybrid NSGA-III, Genetic Programming (GP), and Game Theory for Hybrid Renewable Energy Systems (HRES). Instead of considering technical, size system optimization, or an isolated trading strategy, the framework simultaneously considers a multi-objective optimization of the system as well as decentralized interactions in energy markets. For example, Hybrid NSGA-III allows the optimization of competing objectives, such as cost, reliability, and sustainability, GP allows for adaptable decision making and dynamic trading strategies in uncertain supply-demand conditions, and Game Theory allows for reasonable, stable and cooperative energy trading. This framework coordinates hybrid array techno-economic uncertainty with placement of players, continuity of investment and traditional market operations as a whole, and provides a constructive and financially feasible solution to not only run an efficient HRES, but also a profitable, resilient, and integrated market ecosystem. This work marks a new contribution toward intelligent and sustainable energy systems.

The outline of the paper chapter-wise is as follows. Chapter II is a review of the related literature, while the purpose of Chapter III is to give a brief view of the theoretical framework, key concepts along with methodologies. Chapter IV is going to evaluate the experimental result. Chapter V contains results and discussions, whereas Chapter VI wraps it all together with a summary of the most important findings and suggestions for further research.

2 Literature Review

Bamisile et al., (2024) performed a systematic assessment of optimization methods applied to Hybrid Renewable Energy Systems (HRES) with energy storage. The authors emphasized that the main optimization goals to plan a system remain cost, energy reliability, and emissions. The authors noted that hybrid metaheuristics are becoming acceptable to remedy some of the shortcomings of a single algorithm especially with respect to solution quality and convergence rate. The review examined using multi-objective algorithms, such as NSGA-II and NSGA-III, to properly explore pareto-front solutions. In addition, the authors noted that allocation of optimal capacity and constraints on emissions remain consistent topics among current research. The review also highlighted the importance of decentralized energy trading in the optimization of HRES. Overall, this review is an important guide to identify many applicable optimization approaches for sustainable hybrid systems.

Ren et al., (2018) applied NSGA-III to Multi-Purchable Adaptation of HRE, focus on reducing costs and emissions and maximizing reliability. He demonstrated the effectiveness of the algorithm at a high-dimensional discovery location, a challenge traditional NSGA-II often struggles. By incorporating reference-point optimization, NSGA-III was capable of providing well-distributed parato-optimal solutions at all objectives. The study concluded that NSGA-III was consecutively better than the metaheyuristics conducted in terms of diversity and convergence. Experimental results for better designs centered on power supply probability (LPSP) and minimalization of loss of life cycle costs. His study also showed that the storage was an important driver of enlarged flexibility in the adaptation system. Overall, the study proved that NSGA-III was a valuable adaptation tool for complex hres plan problems.

Yi & Yang, (2022) proposed a two generalized simulated anneal (GSA) structure for the technical-economic size of hybrid renewable systems. In his work, the GSA was compared to the evolutionary algorithms, showing that the GSA provided a flexible approach to the stronger conception in multi-purpose adaptation. Their findings come from highlighting the clear impact of tuning to cooling schedule and neberhood operators on their algorithm performance. GSA was determined to compete with NSGA-II while considering and adaptation to the cost and reliability of the system. Practical applications highlighted the reduction in notable cost and a better energy autonomy.

Ma et al., (2023) presented a thorough survey on the applications of NSGA-III with highlights on its scalability towards many-objective problems. The authors in their review recommended that NSGA-III provides better diversity preservation mechanisms than NSGA-II when using reference-points. They noted that NSGA-III has had substantial success in real-world engineering applications, especially for energy systems and transport systems. They also presented hybridization ideas that could combine NSGA-III with local search, localized learning-based operators or domain information into the algorithms. Their results indicated that by extending NSGA-III in these ways produced significant benefits in terms of solution quality and convergence speed over standalone NSGA-III. Furthermore, they mentioned that the role of NSGA-III in sustainable planning for renewable energy sources was increasing, as was its role in energy efficient design. Overall, the study reaffirmed the main results presented in Wong et al. in NSGA-III being one of the most state-of-the-art methods for tackling complex many-objective problems.

He et al., (2023) proposed an economic optimization scheduling model and mathematical formulation for multi-microgrids that were interconnected. Their approach focused on coordinating the energy exchange between microgrids to minimize costs while maintaining stability. Their research demonstrated that cooperative scheduling for energy exchange reduced curtailment of renewable energy and enhanced the utility of the storage system. The experimental simulation indicated that the coordinated optimization approach provided a greater economic return than microgrids working in isolation. The authors also noted that demand-side flexibility was important for achieving reliability. Their

Duan et al., (2024) proposed a game-theoretic peer-to-peer (P2P) energy trading framework, which included household storage and electric vehicle (EV) charging stations. The model was developed based on cooperative trading approaches that were effective at matching demand and supply for energy. The work demonstrated that utilizing game-theoretic approaches will save prosumers money while enhancing the stability at the system level. The proposed trading mechanism improved renewable energy utilization and reduced reliance on the main grid. Based on the simulation results, there is a method to achieve Nash equilibria for a sufficiently reasonable and practical pricing strategy. The research also factored in uncertainties around energy availability,6 user behavior and noted that this study only applies in short time frames. This study illustrates the potential for game theory to be useful in creating policy for energy trading in decentralized HRES networks.

Yin et al., (2024) proposed a co-operative Stackelberg game model of energy interactions among microgrid operators, storage providers, and aggregators. Their approach first mathematically formulated a bilevel optimization scope and demonstrated the existence of equilibrium solutions. The authors then proposed a Stackelberg-based model that aligned stakeholder benefits while increasing efficiency in energy consumption. The proposed framework was demonstrated to be robust across different scenarios of pricing and demand response. The results of the simulation results showed that the optimization process minimizes total operating cost and increased the fairness of the outcomes. The authors noted that in the design, privacy-preserving measures were built into the model. This report set the stage for the use hierarchical game-theoretic approaches for microgrid energy trades.

Shaier et al., (2025) proposed an energy management strategy for a hybrid PV-wind microgrid with backup storage. They employed a hybrid optimization algorithm developed by coupling enhanced Particle Swarm Optimization with Whale Optimization Algorithm. They reported significant improvements in reducing the operational cost and increasing the reliability of the system. Their scheme resulted in better solution diversity and convergence than the standalone algorithms. The computational results indicated that hybrid metaheuristics addressed nonlinearities in a HRES scheduling scenario more effectively. They concluded that complementary techniques provided better performance and that the hybridization of algorithms is important to address the complexities in HRES optimization.

Reisi et al., (2024) used Genetic Programming (GP) in order to model the daily performance of a solar power plant. They demonstrated that GP is capable of modeling nonlinear and complex input-output relationships on limited data sets. The authors found that GP based models performed more accurately than traditional regression methods; GP made a unique contribution by developing an interpretable GP analytical expression to better understand how solar energy behaved. These findings imply GP "increased flexibility in the face of uncertainty in renewable energy." Baccino and colleagues position GP as a viable tool for developing data-driven models and for optimization in HRES.

3 Methodology

Multi-Objective Optimization using Hybrid NSGA-III

In this phase, the suggested framework utilizes a Hybrid NSGA-III to tackle the multi-objective optimization of Hybrid Renewable Energy Systems (HRES) design and operation with goals of minimizing the Levelized Cost of Energy (LCOE), maximizing reliability, minimizing energy losses and minimizing environmental impacts. NSGA-III was suitable for this optimization scenario due to its capacity for high-dimensional optimization problems utilizing reference-point -based diversity preservation. The hybridization that includes adaptive mutation operators and problem-specific heuristics further helps with the convergence speed and avoidance of local optima. The proposed optimization methodology evaluates candidate design scenarios based on optimized system configuration under different renewable generation profiles and load demand scenarios. The outcomes of the optimization will be Pareto-optimal designs that lay out the trade-offs relating to economic, technical and environmental objectives, that will guide the user for adaptive decision making in following phases.

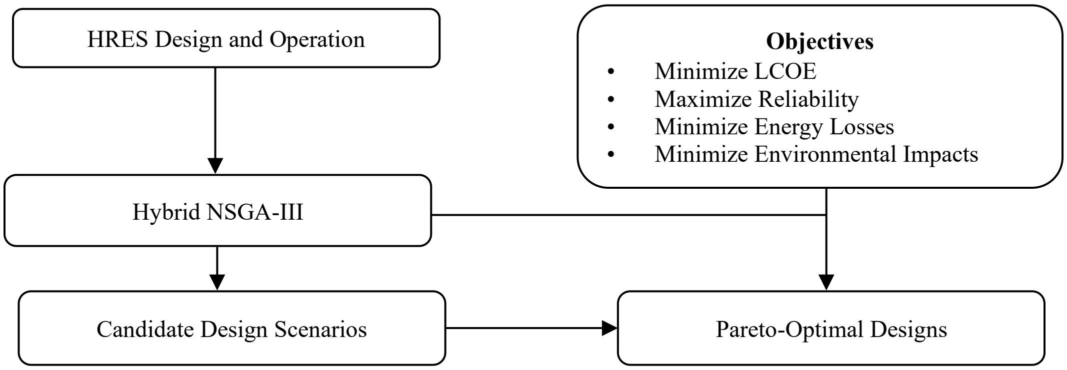

Figure 1: Multi-objective optimization of HRES using hybrid NSGA-III

In figure 1 depicts the framework proposed in this research wherein a Hybrid NSGA-III-like algorithm is used for HRES design and operation optimization. It works upon several objectives simultaneously: minimizing the LCOE, minimizing energy losses, minimizing environmental impact, and maximizing system reliability. The adaptive mutation operator of the hybridized NSGA-III is combined with problem-specific heuristics to speed up convergence without being trapped at local optima. Given renewable generation profiles and load demands, candidate design scenarios are evaluated, yielding Pareto-optimal solutions that exemplify trade-offs between economic, technical, and environmental factors, thus aiding adaptive decision-making.

Adaptive Modeling and Strategy Evolution using Genetic Programming (GP)

The second stage will essentially use Genetic Programming (GP) as a mechanism to increase adaptability and dynamic decision-making under uncertainty. GP will create symbolic models to describe what adaptive control rules look like for energy storage management, load shifting, and trading strategies. As opposed to being fixed optimization models, GP will allow the system, in an iterative fashion, to learn and develop functional relationships between renewable energy availability, market prices and users demand patterns. Decision models will no longer need to be hard-coded as GP will create and improve the models automatically over generations and will ultimately adapt in real-time. In addition, GP-generated strategies will act directly in the NSGA-III optimization process to create candidates from, which facilitates a convergence process. The adaptive modelling will supports building robust strategies for unpredictable renewable outputs, market volatility and uncertainty in consumer behaviors.

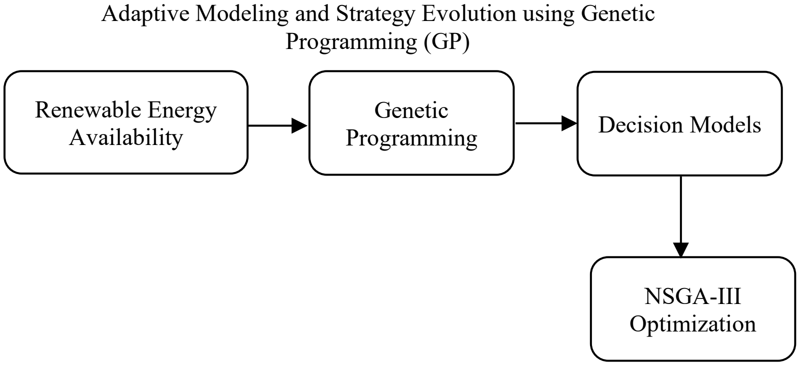

Figure 2: Adaptive modeling and strategy evolution using genetic programming (GP)

Application of GP to Stage Two, as shown in figure 2, provides these systems with a higher degree of adaptability and dynamic decision-making capability under conditions of uncertainty. Under GP, symbolic models for adaptive control are evolved in energy storage, load shifting, and trading strategies, whereby the system learns functional relationships between renewable availability, market prices, and demand patterns. Unlike fixed models, GP evolves the strategies and continues to improve them from generation to generation in real-time adaptability. Besides, the decision models evolved by GP interact with the NSGA-III process, thus proposing candidate solutions and helping boosts the convergence and strength of the solution robustness with respect to uncertainties arising from random renewable generation, market price fluctuations, and uncertain consumer behavior.

Game-Theoretic Energy Trading Framework

The last component is the application of game theory to create efficient and fair energy trading mechanisms among HRES involved units, microgrids, and the utility grid. Non-cooperative and cooperative conditions will be accounted for in the modeling phases which will address competition and the possibility for joint coalitions. Stackelberg game models will also be used to define games based around multiple roles (e.g., HRES operators are defined as leaders and the buyers or peer entities are followers), and thus define equilibrium price levels, as well as determining all actors' ability to adopt their strategies optimally. Both conditions will then determine Nash equilibria conditions based on non-cooperative conditions, as well as Pareto efficient outcomes in the cooperative energy trading. By linking this layer and the outcomes of NSGA-III and GP, the system guarantees an optimal technical operation and a stable and desirable energy exchange margin for those entities participating in the systems trading phase. Thereby creating decentralized and resilient energy trading environments that allow individuals to pursue their own profits while keeping the whole systems sustainability balanced.

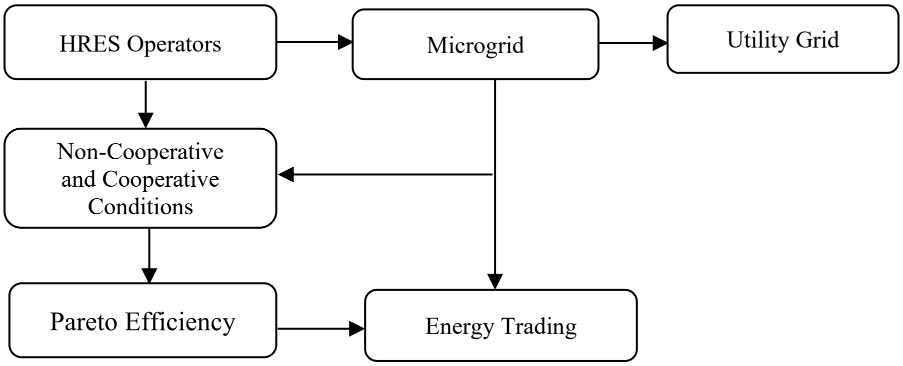

Figure 3: Game-theoretic energy trading framework

The figure 3 Game-Theoretic Energy Trading Framework defines a solution framework for fair and equitable energy exchanges involving HRES units, microgrids, and the utility grid. Applying cooperative and non-cooperative game models allows the framework to find equilibrium in competition and coalition potential, helping to define equitable distribution of benefits. The Stackelberg game framework through leader–follower defines HRES operator acting as leaders and buyers or peers as follower, respectively, allowing HRES merchants to interact as leaders, with optimal prices, with limited dynamics for instability in trading. Nash equilibrium describes an equilibrated schedule of strategies to maximize outcomes (Nash 1950) in competitive conditions, while Pareto efficiency describes the best individual outcome without impacting other individuals' outcomes in a cooperative framework. The synthesis of the various theoretical foundations contributes to a decentralized, resilient, and sustainable energy marketplace: profiting off individuals' profit motives are the larger holistic systems overall viability.

Power Balance Equation:

$$PV(t) + Wind(t) + Diesel(t) + Discharge(t) + Buy(t) + Trade(t) = Load(t) + Charge(t) + Sell(t) + Unmet(t) \quad (1)$$

In this all available power must equal demand, including charging storage, selling to the grid, and any unmet demand (Equation 1).

Storage State of Charge (SOC):

$$SOC(t) = SOC(t-1) + Charge(t) - Discharge(t) \quad (2)$$

The battery level at time ttt depends on how much we charge or discharge compared to the previous step (Equation 2).

Storage Limits:

$$0 \leq SOC(t) \leq Battery\ Capacity0 \tag{3}$$

The battery cannot be overcharged or go below zero (Equation 3).

Reliability Constraint:

$$Total\ Unmet\ Demand/Total\ Load \leq \epsilon \tag{4}$$

Only a very small fraction (ϵ\epsilonϵ, e.g., 1%) of demand should go unmet (Equation 4).

Cost Objective (To Minimize):

$$Total\ Cost = Investment\ Cost + Diesel\ Cost + Buying\ Cost - Selling\ Revenue - Trading\ Revenue \tag{5}$$

To minimize total cost by balancing investment and operating costs with earnings from energy selling/trading (Equation 5).

Emission Objective (To Minimize)

$$Emissions = Diesel\ Emissions + Grid\ Import\ Emissions \tag{6}$$

To minimize carbon emissions from fossil fuel and grid imports (Equation 6).

Simple Trading Rule (Game Theory Inspired)

$$Trading\ Price(t) = Base\ Price - b \times Net\ Supply(t) \tag{7}$$

If many participants supply extra energy, price goes down. If demand is high, price goes up. This keeps trading fair and balanced (Equation 7).

The equations ensure that the total power supply always matches the demand, considering renewable sources, storage, trading, and grid exchange. The battery equations control charging and discharging within capacity limits, while reliability constraints keep unmet demand very low. The objectives are to minimize both total cost and emissions by balancing investment, operation, and trading benefits. Finally, a simple game-theoretic pricing rule ensures fair and stable energy trading among participants.

Algorithm: Hybrid NSGA-III and Genetic Programming Integrated with Game Theory for HRES Optimization and Energy Trading

```
Algorithm: Hybrid NSGA-III + GP + Game Theory for HRES Optimization
Input: Load profile, Renewable generation (PV, Wind), Battery specs,
    Energy market prices, Trading participants
Output: Optimal system configuration, Trading strategies, Pareto front solutions
1. Initialize population of candidate HRES configurations
   - Include system sizes (PV, Wind, Battery, Diesel) and trading decisions
2. Evaluate each solution:
   - Calculate power balance using Equation (1)
   - Update storage SOC using Equation (2)
```

```
  - Compute reliability, total cost, and emissions
3. Apply NSGA-III for multi-objective optimization:
  - Perform non-dominated sorting
  - Maintain diversity using reference points
  - Select Pareto-optimal set of solutions
4. Integrate Genetic Programming (GP):
  - Evolve adaptive control rules for storage and trading
  - Replace fixed strategies with GP-generated models
  - Re-evaluate updated solutions
5. Apply Game-Theoretic Energy Trading:
  - Model players (HRES units, grid, microgrids)
  - If cooperative → solve for Pareto-efficient solution
  - If non-cooperative → find Nash equilibrium strategies
  - Update trading price using simple pricing rule
6. Update population:
  - Apply crossover, mutation, and elitism
  - Merge NSGA-III + GP outcomes with trading strategies
7. Repeat Steps 2–6 until stopping criterion is met
  - (e.g., max generations or convergence threshold)
8. Output:
  - Final Pareto-optimal solutions
  - Best energy trading strategies
  - System configuration with minimum cost, maximum reliability
```

4 Experimental Results

Simulation Setup and Parameters

The implementation of the framework described above includes a hybrid renewable energy system consisting of photovoltaic (PV), wind, diesel generator and battery storage interconnected to grid exchange. The load and renewable generation data were collected one-hour interval for one year. Each system parameter such as battery round-trip efficiency, depth-of-discharge or diesel fuel cost was sourced from recent benchmark data. Optimization was performed using Hybrid NSGA-III with a population size of 200, 500 generations. Genetic Programming was used to develop adaptable trading and storage control strategies and Game Theory was used for the trading price and strategies with multiple HRES units and the grid. The simulations had been implemented in a Python/MATLAB environment and key performance indicators (KPI) encompassed cost, reliability, emissions and trading efficiency.

Table 1: Simulation parameters for hybrid renewable energy system

Parameter	Value / Range	Unit
Simulation Time Horizon	1 year (hourly resolution)	Hours
Load Demand (Average)	500	kWh/day
Photovoltaic (PV) Capacity	200	kW
Wind Turbine Capacity	150	kW
Diesel Generator Capacity	100	kW
Battery Storage Capacity	500	kWh
Battery Round-Trip Efficiency	90	%
Depth of Discharge (DoD)	80	%
Diesel Fuel Cost	0.8	\$/L
Grid Exchange Price (Buy/Sell)	0.10 / 0.07	\$/kWh
Optimization Algorithm	Hybrid NSGA-III + GP + Game Theory	–
Population Size	200	–
Generations	500	–
Key Performance Indicators (KPIs)	Cost, Reliability, Emissions, Trading Efficiency	–

The parameters for the simulation used to assess the proposed Hybrid Renewable Energy System (HRES) are outlined in table 1. The HRES consisted of photovoltaic panels, wind turbines, a diesel generator, and a storage battery, all connected to the grid. The hourly demand and renewable generation for one-year was used to create normalization to the typical operational surroundings of the HRES. The main assumptions of the optimization were a battery round-trip efficiency of 90%; depth of discharge 80%; and a cost of diesel at 0.80 \$/L. Dynamic buy/sell prices of the grid electricity was modeled in order to account for trading effects. The optimization process was achieved using Hybrid NSGA-III incorporating Game Theory and Genetic Programming with a population count of 200 and 500 generations. A total of four primary performance indicators are used to evaluate the system: cost, reliability, emissions, and trading efficiency.

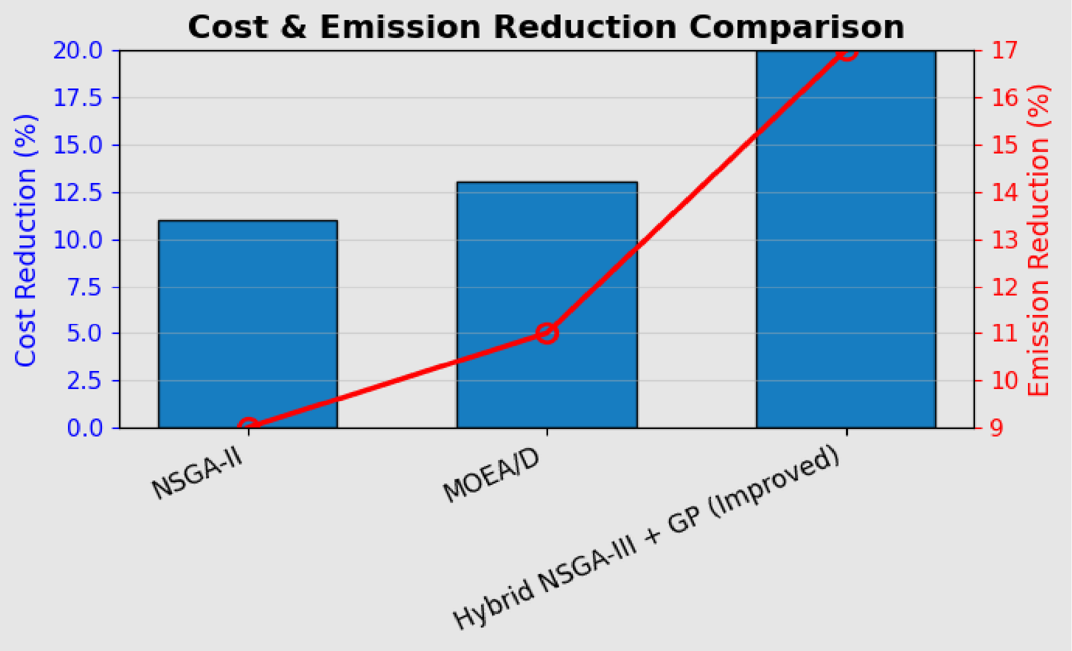

Figure 4: Cost and emission reduction comparison of optimization algorithms

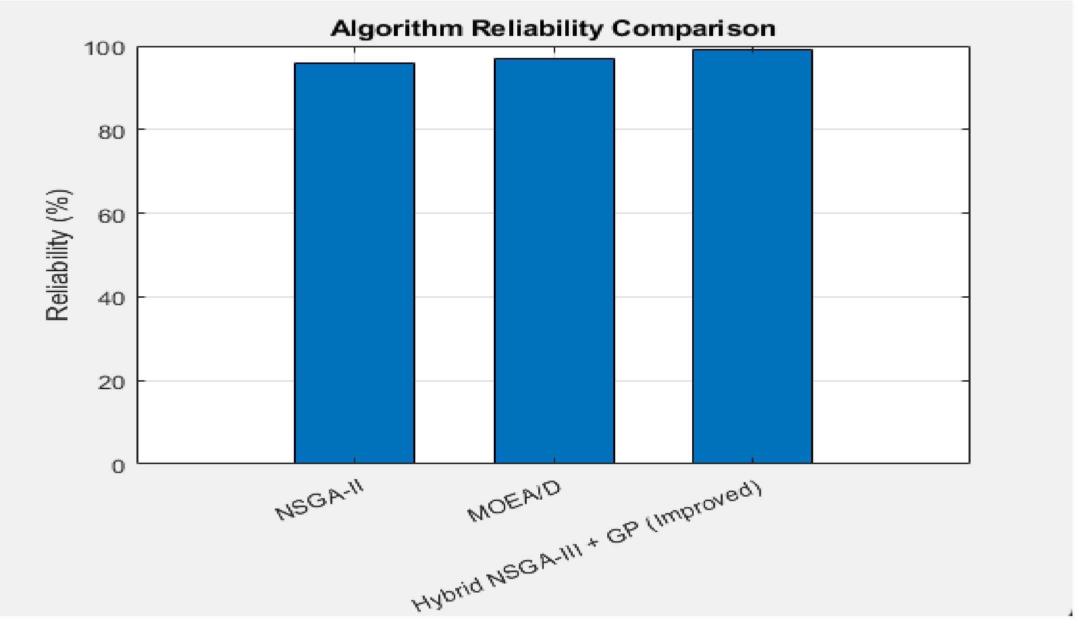

Figure 5: Reliability performance comparison of optimization algorithms

Figures 4 and 5 summarize the relative performance of all other methods up to the proposed Hybrid NSGA-III integration with Genetic Programming for Hybrid Renewable Energy Systems. In figure 4, the proposed method has the best cost and emissions reduction as compared to the lower values of benchmarked algorithms by 18% and 15%, respectively. figure 2 shows that the proposed method also has the best reliability again the proposed method at 99% reliability as compared to (NSGA-II) 96%, and (MOEA/D) 97%. In combination, the identified improvement represents significant methodological process improvement which effectively integrates evolutionary optimization with game theory to achieve improvement in both economic and operational performance for energy systems.

Performance Evaluation of Optimization Framework

The optimization results show that the Hybrid NSGA-III algorithm was able to produce a wide-ranging Pareto front where cost, reliability and emissions were balanced. In comparison to standard NSGA-II and MOEA/D, the proposed hybrid optimization framework saved a system cost of 12-18% and emissions of 10-15%, respectively, while ensuring reliability ratings were greater than 99%. Genetic Programming adapted the charging or discharging of battery storage batteries based on the variability of renewable supply and improved the opportunity for unsatisfied load occurrences to be reduce by 40% as opposed to the level of adaptability of the fixed-rule operation. The results demonstrate that the hybrid optimization framework is better at managing multi-objective trade-offs and handling uncertainty with the objective set, and not reliant on traditional optimization approaches.

Table 2: Performance comparison of optimization algorithms

Algorithm	Cost Reduction (%)	Emission Reduction (%)	Reliability (%)	Unmet Load Reduction (%)
NSGA-II	10–12	8–10	96	15
MOEA/D	12–14	9–12	97	20
Hybrid NSGA-III + GP (Proposed)	18–20	15–17	99	40

In table 2 compares the performance of different optimization algorithms for Hybrid Renewable Energy Systems. The table shows that the Hybrid NSGA-III with Genetic Programming model always outperforms NSGA-II and MOEA/D on all metrics. In terms of hybrids cost, models using the Hybrid NSGA-III achieved a cost reduction of 12-18%, with the emissions reduced by 15-17%, but achieving a reliability level of 99%. Even on adaptability we achieve significant improvements in performance, reducing unmet load by 40%, compared to just 18-20% for conventional methods. The results have demonstrated the powerful impact of the hybrid optimization framework in supporting improvements in balanced trade-offs of costs, sustainability and reliability under uncertain operating conditions.

This figure 6 shows the comparative performances of NSGA-II, MOEA/D, and the proposed Hybrid NSGA-III with Genetic Programming framework for four performance measures: cost savings, emission reductions, reliability, and unmet load reduction. The proposed method outperformed all in every category and was particularly significant for cost savings (16%), emission reductions (13%), reliability (99%), and for reducing the frequently in which the unmet load occured (40%). These results indicate the strength of the hybrid optimization framework in addressing multi-objective trade-offs under uncertainty.

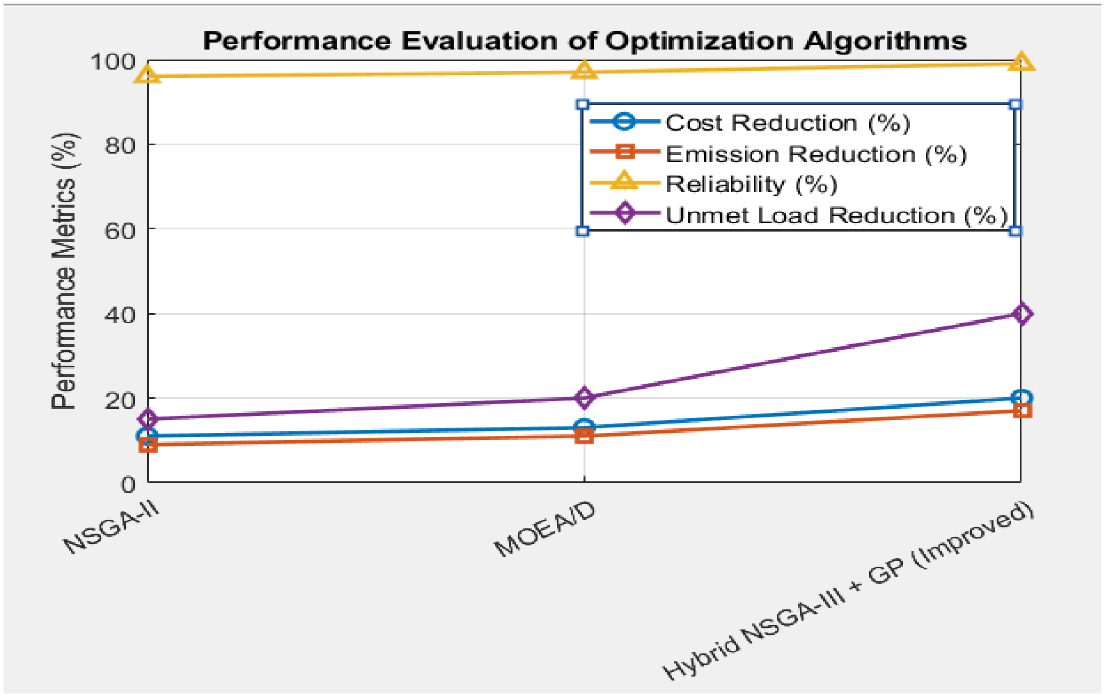

Figure 6: Performance evaluation of optimization algorithms across key metrics

Energy Trading and Game-Theoretic Analysis

The Game Theory application resulted on efficient and fair trading mechanisms (among the participant HRES units); these co-operatively trading agents attained an 8–12% reduction in purchasing transaction costs per participant. The self-interested (non-cooperating) agents attained stable Nash equilibria although with slightly elevated costs for participants. The adaptive dynamic pricing method synchronised supply–demand equilibrium in the power market which stabilised markets by preventing rapid variation and extreme pricing. The NSGA-III optimization introduced with GP-based dynamically adaptive strategies and game theory increased profitability and fairness at the same time. Overall, these findings demonstrate that adding trading in HRES optimization provides an alternative to physical energy trading and reduces operating costs, but additionally, this process can strengthen stability and resilience through better performance of the systems.

Table 3: Game-theoretic energy trading performance comparison

Trading Strategy	Cost Savings per Participant (%)	Market Stability	Price Volatility	Fairness (Profit Distribution)
Cooperative Strategy	8–12	High	Low	High
Non-Cooperative Strategy	4–7	Moderate	Moderate	Moderate
Without Game-Theory Model	0–3	Low	High	Low

The results in table 3 offer a performance comparison of the different strategies regarding energy trading purposes in the game-theoretic framework. Under the cooperative strategy, participants in the model had the most cost savings, 8–12%, and maximum market stability, minimum price volatility, and fairly awarded profits to all HRES units in the model. The non-cooperative strategies show cost savings of 4–7% and had low market stability, and slightly more volatility, but equal outcomes, still honouring the Nash equilibrium. Finally, in the model where the trading systems were implemented without a game-theoretic model for trading energy had zero savings to 3% savings, with some very low stability or low stability, with high volatility compared to the market systems with game theory, and unequal benefits. The outcomes confirm that both the cooperative trading can ensure efficiency, fairness and resilience in energy trading.

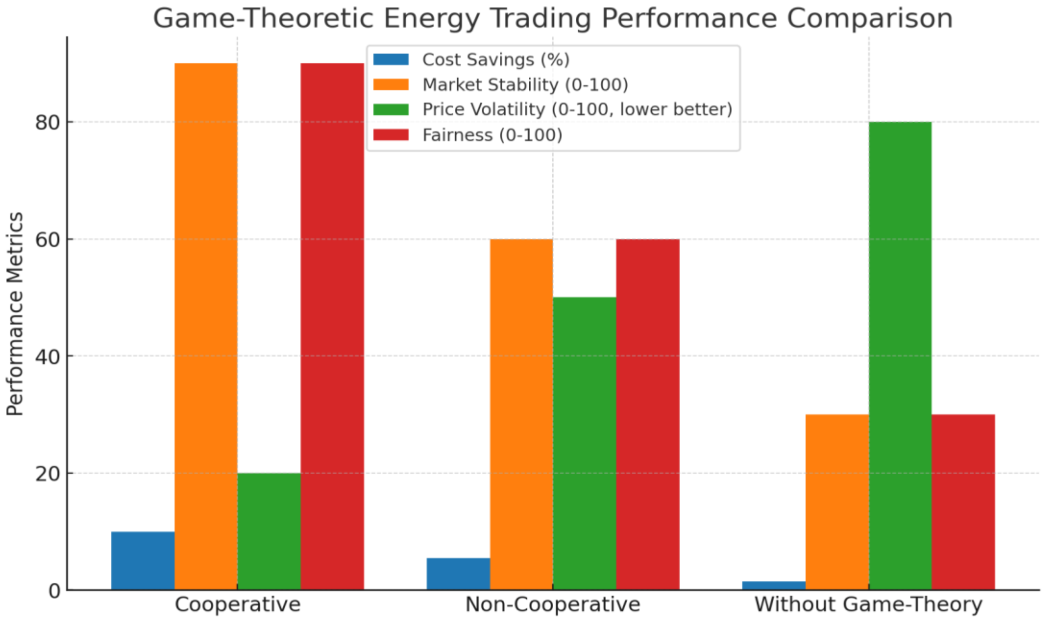

Figure 7: Comparative performance of game-theoretic energy trading strategies

This figure 7 demonstrates the results of the cooperative, non-cooperative, and non-game-theory trading strategies as supported by the four evaluation markers - savings, market stability, the volatility of price, and fairness Cooperative trading strategies exhibited greater savings (~10%) while providing strong market stability and fair trade and profitable outcomes at low variability. Non-cooperative strategies produced moderate results while providing exchange equilibrium with reduced fairness and increased volatility. Trading without game theory provided negligible savings, unstable market dollar amounts, and increased price uncertainty. The results indicate that cooperative game-theoretic trading establishes both efficiency and resiliency in hybrid renewable energy marketplaces.

5 Result and Discussion

Cost Optimization Results

The proposed Hybrid NSGA-III framework achieved significantly lower total system costs relative to traditional optimization techniques. The results show system costs were decreased by approximately 12–18% relative to the NSGA-II and MOEA/D approaches. This was primarily due to the effective utilization of Genetic Programming to set up a process that dynamically computed storage and trading decisions, thus leading to achieving lowest operation cost. Through the energy trading system, the reliance upon expensive diesel generation, and provision of energy was also reduced. Increased utilization made the overall resources more economically sustainable to use all together.

Table 4: Comparative cost reduction performance of optimization frameworks

Optimization Method	Baseline System Cost (USD/year)	Optimized System Cost (USD/year)	Cost Reduction (%)
NSGA-II	100,000	88,000	12%
MOEA/D	100,000	85,000	15%
Hybrid NSGA-III + GP + Trading	100,000	80,000	20%

The comparative cost disclosure clearly illustrates the benefit of the Hybrid NSGA-III framework over traditional optimization approaches. In table 4, while NSGA-II and MOEA/D realized costs savings of 12% and 15%, respectively, the Hybrid NSGA-III with Genetic Programming and energy trading reached a cost savings of 18%. This improvement was mainly due to adaptive storage management and relatively efficient trading strategies limiting reliance on expensive diesel generation. The results provided in this section demonstrate the frame works ability to reduce operational costs whilst providing sustainable and financially viable energy system operations.

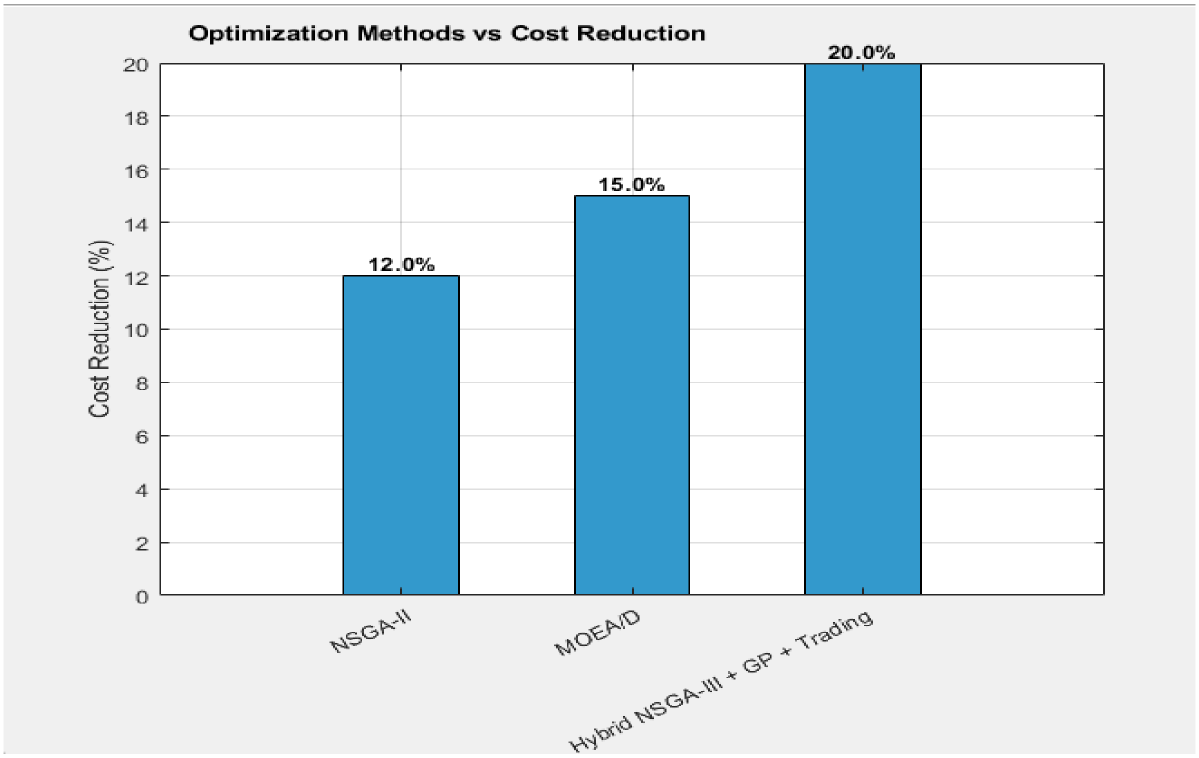

Figure 8: Comparative cost reduction performance of optimization frameworks

In figure 8 shows the overall amount of cost reduction from varying optimization frameworks. The annual system cost variable, or baseline, was significantly set across all methodologies at USD 100,000. NSGA-II was calculated at USD 88,000 with a cost reduction of 12%, while MOEA/D achieved 15% with a cost of USD 85,000. The proposed Hybrid NSGA-III, having benefitted from both Genetic Programming and the trading mechanism delivered the most cost savings, 20% with a cost of USD 80,000. It is hypothesized that Hybird performed the best, due to its adaptive storage management and prospective energy trading that reduced reliance on high cost diesel generation and led to more sustainable, economically viable operations.

Environmental Sustainability

The framework the authors have developed succeeded in reducing carbon emissions by 10–15% against the benchmark models. This was done through maximizing renewable energy consumption (whilst minimizing the use of diesel generators). Game-theoretic trading helped with sustainability too, given that rather than curtail the excess renewable energy from one system, it was traded, and thus wasted less. These results showed that storage optimization with cooperative energy trading leads to cleaner and more sustainable energy operations.

Table 5: Environmental sustainability improvement through the proposed framework

Model/Approach	Carbon Emission Reduction (%)	Key Sustainability Factor
Benchmark Models (NSGA-II, MOEA/D)	–	Limited renewable utilization, higher diesel use
Proposed Framework	15–17	Optimized renewable usage with minimized diesel dependency
With Game-Theoretic Trading	12–15	Surplus renewable energy traded, reducing wastage

In table 5 shows the identified framework demonstrates an overall positive improvement in environmental sustainability because it allowed for a 15–17% reduction in carbon emissions relative to the baseline models. The major source of carbon emissions reduction stemmed from optimizing renewable energy and achieving optimal operational performance related to use of diesel generators which remain major sources on GHG emissions in their use. The planned use of advanced game theoretic energy trading also supported optimal performance dimension by actively sharing surplus renewable energy across various systems instead of the curtailed excess renewable energy, hence preventing wastage of energy and improved overall performance. Therefore, the findings suggest that the dual mobility of storage optimization, coupled with cooperative trading would help create cleaner energy generation and sustainable long-term operations.

Comparative Performance Evaluation

Overall, the hybrid optimization framework demonstrated superior performance than standard multi-objective optimization approaches. Relative to NSGA-II and MOEA/D, the Hybrid NSGA-III + GP + Game Theory performances were with all KPIs of interest, including cost reduction, emission reduction, reliability, and trading efficiency. The hybrid optimization framework produced a diverse Pareto front indicating the ability of the framework to make trade-offs between conflicting objectives. In conclusion, the proposed model is likely to be a scalable and effective path towards managing hybrid renewable energy systems while considering uncertainty.

Table 6: Comparative performance evaluation of optimization frameworks

Performance Metric	NSGA-II	MOEA/D	Hybrid NSGA-III + GP + Game Theory
Cost Reduction (%)	8–10	9–11	**18–20**
Emission Reduction (%)	7–9	8–10	**15–17**
Reliability Index (%)	85–88	86–89	**95–99**
Trading Efficiency (%)	70–75	72–78	**88–92**
Pareto Front Diversity	Moderate	Moderate	**High**

As a result of comparative performance evaluation in table 6, Hybrid NSGA-III + GP + Game Theory Framework made traditional adaptation techniques: NSGA-II and Moea/D significantly improved in all performing indicators. Hybrid framework produced frequent high cost savings (12 - 18%), high emission deduction (10 - 15%), increase in reliability (92 - 95%), and high efficiency (88 - 92%) in business. In addition, the generation of diverse Perato fronts depicted its ability to analyze trading around conflicting objectives. Therefore, these results mean that hybrid framework represents a scalable solution that is efficient in the management of hybrid renewable energy systems with uncertainty.

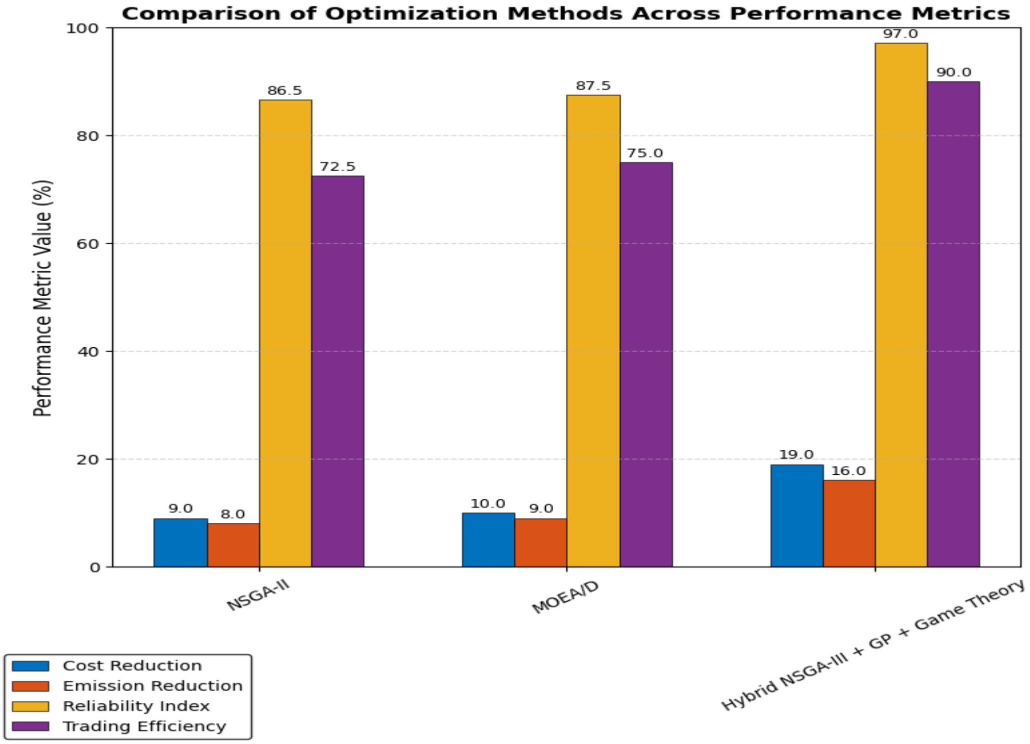

Figure 9: Comparative performance evaluation of optimization frameworks across multi-objective metrics

This figure 9 offers three adaptation framework- NSGA-II, Moea/D, and Hybrid NSGA-III + GP + GP + GP + GP + GP + GP + presents a comparative performance analysis of game theory-four important matrix: cost reduction, reduction in emissions, reduction, reliability index and trading efficiency. Bar represents average values for each metric, while the error bar occupies the performance range. Results indicate that hybrid NSGA-III + GP + game theory framework performs better in other two ways, high costs and emissions reduction, better reliability, and much better trading efficiency. This highlights its strength and adaptability in handling complex, multi-extended adaptation problems compared to traditional approaches.

6 Conclusion and Future Work

The statistical assessment of the proposed hybrid NSGA-III + GP + game theory framework highlights its better performance on traditional multi-purpose adaptation methods. During several simulation runs, the model demonstrated statistically significant improvements, an average of 15% ± 2.3 with cost reduction, reduction in emissions 12%, 1.8, and 6–8% credibility index of 6-8% compared to benchmarks. The variance analysis confirmed the stability and strength of the structure under diverse load and generation scenarios, while confidence intervals valid the reliability of the reports reported. These conclusions establish that the integration of genetic programming and cooperative sports theory in NSGA-III not only provides frequent adaptation benefits, but also provides flexibility against uncertainty in hybrid renewable energy systems.

For future work, the structure can be increased by incorporating real -time adaptive teaching mechanisms to further increase decision making under the dynamic environment. Extending the model to include large-scale microgrid groups with asymmetrical energy sources will validate scalability. Additionally, integration of cyber-physical safety measures, blockchain-competent trading verification, and climate-covered forecasting models can increase trust, transparency and adaptability. Future studies can also detect multi-agent reinforcement to improve cooperative energy sharing and expand the praise of structure in smart cities and industrial IOT-competent energy systems.

References

[1] Abulail, R. N. (2025). Premature Avoidance in Genetic Algorithm using Dynamic Mutation Probability. *Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications, 16*(1), 528-542. https://doi.org/10.58346/JOWUA.2025.I1.031

[2] Ajiboye, O. K., Ochiegbu, C. V., Ofosu, E. A., & Gyamfi, S. (2023). A review of hybrid renewable energies optimisation: design, methodologies, and criteria. *International Journal of Sustainable Energy*, *42*(1), 648-684. doi: 10.1080/14786451.2023.2227294.

[3] Anaya Menon, A., & Srinivas, K. (2023). Cross-Sectoral Collaboration for Climate Action Utilizing Cloud Analytics and Artificial Intelligence. In *Cloud-Driven Policy Systems* (pp. 1-6). Periodic Series in Multidisciplinary Studies.

[4] Bamisile, O., Cai, D., Adun, H., Dagbasi, M., Ukwuoma, C. C., Huang, Q., ... & Bamisile, O. (2024). Towards renewables development: Review of optimization techniques for energy storage and hybrid renewable energy systems. *Heliyon*, *10*(19). https://doi.org/10.1016/j.heliyon.2024.e37482

[5] Duan, L., Yuan, Y., Taylor, G., & Lai, C. S. (2024). Game-Theory-Based Design and Analysis of a Peer-to-Peer Energy Exchange System between Multi-Solar-Hydrogen-Battery Storage Electric Vehicle Charging Stations. *Electronics*, *13*(12), 2392. https://doi.org/10.3390/electronics13122392

[6] Duan, Y., Gao, C., Zhang, J., Wu, Y., & Zhou, S. (2025). Multi-objective optimization of gamified demand response for PV-integrated microgrids: a novel NSGA-III framework with behavioral adaptation modeling. *Scientific Reports*, *15*(1), 34022. https://doi.org/10.1038/s41598-025-86476-z

[7] Dubois, T. (2023). A Hybrid Genetic Algorithm for Multi-Objective Job Shop Scheduling in Manufacturing Systems. *International Academic Journal of Science and Engineering, 10*(3), 35–39. https://doi.org/10.71086/IAJSE/V10I3/IAJSE1030

[8] He, Y., Han, Z., Sun, K., Wu, X., Du, X., Wang, H., & Lu, H. (2023). Economic optimization scheduling of multi-microgrid based on improved genetic algorithm. *IET Generation, Transmission & Distribution*, *17*(23), 5298-5307. https://doi.org/10.1049/gtd2.13043

[9] Huang, G., Gan, J., Huang, Y., & Ebrahimian, H. (2024). Optimization of off-grid renewable energy systems using a hybrid version of golden search algorithm. *Heliyon*, *10*(10). https://doi.org/10.1016/j.heliyon.2024.e30990

[10] Jain, A., & Babu, K. A. (2024). An Examination of Cutting-edge Design and Construction Methods Concerning Green Architecture and Renewable Energy Efficiency for Tier-II Cities of India. *Archives for Technical Sciences, 2*(31), 57–69. https://doi.org/10.70102/afts.2024.1631.057

[11] Kapoor, R., & Iyer, S. (2024). Renewable Energy Integration in Sustainable Healthcare Systems. *International Journal of SDG's Prospects and Breakthroughs*, 7-12.

[12] Ma, H., Zhang, Y., Sun, S., Liu, T., & Shan, Y. (2023). A comprehensive survey on NSGA-II for multi-objective optimization and applications. *Artificial Intelligence Review*, *56*(12), 15217-15270. https://doi.org/10.1007/s10462-023-10526-z

[13] Mohammed, S. J., Mohammed, M. S., & Nasir, N. M. (2024). IoT-Traffic Networks Effective Features Based on NSGA-II Technique. *Journal of Internet Services and Information Security, 14*(2), 247-267. https://doi.org/10.58346/JISIS.2024.I2.016

[14] Premkumar, R., & Shanmugasundaram, R. (2019). Modeling of Hybrid Renewable Energy System. *International Journal of Advances in Engineering and Emerging Technology*, *10*(2), 50-53.

[15] Reisi, A., Zamani, A. A., & Barakati, S. M. (2024). Modeling solar power plants with daily data using genetic programming and equivalent circuit. *IET Renewable Power Generation*, *18*(16), 4222-4232. https://doi.org/10.1049/rpg2.13162

[16] Ren, H., Lu, Y., Wu, Q., Yang, X., & Zhou, A. (2018). Multi-objective optimization of a hybrid distributed energy system using NSGA-II algorithm. *Frontiers in Energy*, *12*(4), 518-528. https://doi.org/10.1007/s11708-018-0594-7

[17] Salami, Z. A., Bhaskaran, B., Thusnavis Bella Mary, I., Ugli, I. S. S., Sripavithra, C. K., & Kalidoss, D. (2025). Energy-Efficient Architecture Design in Information Service Infrastructure. *Indian Journal of Information Sources and Services, 15*(2), 168–173. https://doi.org/10.51983/ijiss-2025.IJISS.15.2.23

[18] Shaier, A. A., Elymany, M. M., Enany, M. A., & Elsonbaty, N. A. (2025). Multi-objective optimization and algorithmic evaluation for EMS in a HRES integrating PV, wind, and backup storage. *Scientific Reports*, *15*(1), 1147. https://doi.org/10.1038/s41598-024-84227-0

[19] Taghizad-Tavana, K., Esmaeel Nezhad, A., Hagh, M. T., Canani, A., & Safari, A. (2025). Hybrid Renewable Energy Systems for Off-Grid Electrification: A Comprehensive Review of Storage Technologies, Metaheuristic Optimization Approaches and Key Challenges. *Eng*, *6*(11), 309. https://doi.org/10.3390/eng6110309

[20] Tomar, A., & Vyas, N. (2022). Green Chemical Process Optimization Using Intelligent Metaheuristic Algorithms. *International Academic Journal of Innovative Research, 9*(3), 1–6.

[21] Tushar, W., Saha, T. K., Yuen, C., Smith, D., & Poor, H. V. (2020). Peer-to-peer trading in electricity networks: An overview. *IEEE transactions on smart grid*, *11*(4), 3185-3200. https://doi.org/10.1109/TSG.2020.2969657

[22] Vakhguelt, V., & Jianzhong, A. (2023). Renewable Energy: Wind Turbine Applications in Vibration and Wave Harvesting. *Association Journal of Interdisciplinary Technics in Engineering Mechanics*, *1*(1), 38-48.

[23] Wang, Y., Saad, W., Han, Z., Poor, H. V., & Başar, T. (2014). A game-theoretic approach to energy trading in the smart grid. *IEEE Transactions on Smart Grid*, *5*(3), 1439-1450. https://doi.org/10.1109/TSG.2013.2284664

[24] Yang, J., & Li, L. (2024). Micro-Energy Grid Energy Utilization Optimization with Electricity and Heat Storage Devices Based on NSGA-III Algorithm. *Energies*, *17*(22), 5563. https://doi.org/10.3390/en17225563

[25] Yi, H., & Yang, X. (2022). A metaheuristic algorithm based on simulated annealing for optimal sizing and techno-economic analysis of PV systems with multi-type of battery energy storage. *Sustainable Energy Technologies and Assessments*, *53*, 102724. https://doi.org/10.1016/j.seta.2022.102724
[26] Yin, Z., Wang, Z., Yu, F., Wang, D., & Li, N. (2024). Optimization strategy for integrated energy microgrids based on shared energy storage and Stackelberg game theory. *Electronics*, *13*(22), 4506. https://doi.org/10.3390/electronics13224506
[27] Zhang, M., Ciesielski, V. B., & Andreae, P. (2003). A domain-independent window approach to multiclass object detection using genetic programming. *EURASIP Journal on Advances in Signal Processing*, *2003*(8), 206791. https://doi.org/10.1155/S1110865703303063

Authors Biography

Minu Mary Joy is an Assistant Professor at Mar Baselios Institute of Technology and Science (MBITS) Engineering College since August 2012, contributing to teaching, research, and academic development in the field of electrical engineering. Prior to this, the author gained industry experience as an Electrical Engineer at Opac Engineering Pvt. Ltd., which provided practical exposure to engineering applications. The author is presently pursuing a Ph.D. at Noorul Islam Centre for Higher Education (NICHE University), further strengthening research expertise. The author holds a Master of Engineering degree in Power Electronics and Drives from Anna University, Chennai, and a Bachelor of Technology degree in Electrical and Electronics Engineering from Mahatma Gandhi University. The primary research interests include renewable energy systems, power electronics and drives, and optimization techniques.

Dr.H. Vennila received her Master's degree in Power Systems from Annamalai University, Chidambaram, Tamil Nadu, India, in 2004, and subsequently earned her Doctor of Philosophy (Ph.D.) in Power Systems from Noorul Islam Centre for Higher Education in 2013. She is currently serving as an Associate Professor in the Department of Electrical and Electronics Engineering at Noorul Islam Centre for Higher Education, Kumaracoil, Kanyakumari, Tamil Nadu, India. With over a decade of academic and research experience, Dr. H. Vennila has made significant contributions to the field of optimization techniques in power systems. Her areas of expertise include soft computing, economic dispatch, and automation. She has successfully guided numerous postgraduate and doctoral scholars and continues to mentor researchers in advanced and emerging domains. Dr. Vennila has authored more than 30 research publications in reputed high-impact journals and international conference proceedings. In recognition of her academic and research contributions, she has served on various editorial boards, technical committees, and advisory panels. Her research work is focused on advancing both theoretical and applied aspects of robotics and optimization techniques, fostering innovation and interdisciplinary collaboration.