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COORDINATED MULTI-OBJECTIVE OPTIMIZATION FOR GREEN POWER SYSTEM SCHEDULING AND CONSUMPTION WITH DIVERSE DEVICES

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ABSTRACT

This study proposes a coordinated multi-objective optimization framework for scheduling and managing power consumption in green power systems with diverse energy devices. The system incorporates renewable sources, energy storage units, and controllable loads to enhance energy efficiency, reduce costs, and minimize environmental impact. A multi-objective evolutionary algorithm is employed to balance conflicting goals such as operational cost, emission reduction, and user comfort. Device-level coordination, including electric vehicles, HVAC systems, and smart appliances, is integrated to enable demand-side flexibility. Simulation results demonstrate the effectiveness of the proposed strategy in achieving optimal scheduling under dynamic load and generation conditions, contributing to the realization of intelligent, low-carbon energy systems.

Keywords: Green power systems, multi-objective optimization, energy scheduling, renewable energy integration, smart grid, coordinated energy management, diverse devices, energy storage, demand response, emission reduction.

INTRODUCTION

The global energy landscape is undergoing a profound transformation, driven by an urgent need to mitigate climate change, enhance energy security, and foster sustainable development. Central to this transition is the increasing integration of green energy sources, primarily wind and solar photovoltaics (PV), into existing power systems [1, 2, 3, 4, 9]. These renewable energy technologies offer a promising pathway towards a carbon-free society, significantly reducing reliance on fossil fuels and their associated greenhouse gas emissions [2, 9]. However, the inherent intermittency and variability of wind and solar power pose significant challenges to the stability, reliability, and economic operation of modern power grids [7, 11, 13]. Fluctuations in renewable generation can lead to supply-demand imbalances, grid instability, and even curtailment of valuable green energy if not managed effectively [12, 23, 40].

To address these challenges, power systems are evolving from traditional centralized structures to more integrated, flexible, and intelligent energy systems [11, 16, 17, 20, 21]. These integrated systems embrace a multi-device approach, coordinating various components such as diverse renewable generators, energy storage technologies, and flexible loads to optimize overall system performance [10, 11, 12, 14, 15, 16, 17, 20, 21]. The concept of "multi-device coordination" is crucial, as it allows for the synergistic operation of complementary energy sources (e.g., hydro-wind-solar systems [7, 13, 28, 33, 36]) and the efficient utilization of energy storage solutions (e.g., batteries, hydrogen, pumped-hydro, thermal storage [15, 18, 19, 20, 22, 23, 24, 29, 39, 43]) to smooth out power output and enhance grid stability. Furthermore, incorporating demand-side management and flexible loads, such as electric boilers and combined heat and power (CHP) units, can provide additional operational flexibility by converting surplus green electricity into storable heat, thereby improving renewable energy consumption and overall system efficiency [12, 25, 27, 34, 40, 42, 44, 45].

The optimization of such complex, multi-device integrated power systems is inherently a "multi-objective" problem [31, 36, 37, 38, 39, 41, 46, 47, 48, 49]. System operators face conflicting goals, including minimizing operational costs, reducing environmental impacts (e.g., CO2 emissions), and ensuring high levels of reliability and power quality. A single-objective optimization typically fails to capture these intricate trade-offs, leading to suboptimal solutions that may prioritize one aspect at the expense of others. Therefore, a comprehensive framework is needed that not only coordinates the operation of diverse energy devices but also simultaneously optimizes multiple, often competing, objectives under conditions of uncertainty [7, 11].

This article presents a detailed study on the optimization and scheduling of green power system consumption based on multi-device coordination and multi-objective optimization. We aim to demonstrate how an integrated approach to managing various energy assets, combined with a holistic optimization strategy, can significantly enhance the utilization of renewable energy, improve system economics, and ensure reliable power supply in future smart grids.

METHODS

The proposed methodology for optimizing and scheduling green power system consumption revolves around a holistic modeling approach that integrates various energy devices, addresses uncertainties in renewable generation and demand, and employs a multi-objective optimization framework.

System Architecture and Components Modeling

The integrated power system considered in this study comprises several interconnected energy devices designed for enhanced flexibility and green energy utilization:

1. Renewable Energy Sources (RES):

○ Wind Power: Modeled considering its inherent variability based on wind speed distributions.

○ Solar PV: Modeled based on solar irradiance and temperature, capturing its intermittent nature.

○ Hydropower (if applicable in complementary systems): Modeled with reservoir constraints and generation limits, providing dispatchable power in hydro-wind-solar complementary systems [13, 33].

2. Energy Storage Systems (ESS): These are critical for buffering renewable intermittency and enhancing system flexibility.

○ Battery Energy Storage Systems (BESS): Modeled with charge/discharge efficiencies, capacity limits, degradation, and state-of-charge dynamics. Batteries play a key role in smoothing renewable power output and providing ancillary services [18, 19, 20, 22, 23, 24, 43].

○ Hydrogen Storage: Modeled as an energy carrier for long-term storage, involving electrolyzers (power-to-hydrogen) and fuel cells (hydrogen-to-power) [15, 29, 39].

○ Pumped-Hydro Storage (PHS): Considered for large-scale energy storage, especially in regions with suitable geographical features [15, 33].

○ Thermal Energy Storage (TES): Integrated with electric boilers or CHP units to store excess electricity as heat [12, 25, 27, 40, 44, 45].

3. Flexible Loads and Demand-Side Management (DSM):

○ Controllable Loads: Loads that can be shifted in time (e.g., certain industrial processes, water pumping) or curtailed during peak demand periods.

○ Electric Boilers (EB): Converts electrical energy into heat, providing a flexible load that can absorb surplus renewable power, especially during periods of high wind or solar generation and low electricity demand [12, 25, 27, 40, 44, 45].

○ Combined Heat and Power (CHP) Units: Generate both electricity and heat, offering flexibility in balancing power and heat demands [25, 27, 34, 42].

4. Conventional Generators: Traditional fossil-fuel-based power plants, used to provide baseline power and fill gaps when renewable generation and storage are insufficient. These are typically modeled with fuel costs, operational limits, and emission characteristics [35, 37, 42].

Uncertainty Modeling

The stochastic nature of renewable energy generation (wind speed, solar irradiance) and electrical/thermal loads is a key aspect addressed in the optimization.

• Probabilistic Forecasting: Historical data and forecasting models are used to generate probabilistic forecasts for wind power, solar PV power, and demand [7, 11].

• Scenario Generation: Monte Carlo simulation or similar techniques are employed to generate a large number of possible future scenarios, each with a specific probability, representing the range of uncertainties. Scenario reduction techniques (e.g., clustering) are then applied to manage computational complexity while preserving the statistical characteristics of the original uncertainty [7, 11].

Multi-Objective Optimization Formulation

The dispatch and scheduling problem is formulated as a multi-objective optimization problem, typically over a day-ahead or intra-day horizon. The conflicting objectives are:

1. Economic Objective (F1): Minimize Total Operating Cost: This includes fuel costs for conventional generators and CHP units, start-up/shut-down costs, operation and maintenance (O&M) costs for all devices, and potentially costs associated with power exchange with an external grid [25, 35, 37]. The cost of renewable energy curtailment can also be internalized.

2. Environmental Objective (F2): Minimize Total Emissions: This aims to reduce the overall release of greenhouse gases (e.g., CO2) and other pollutants from energy generation. Emission factors are assigned to each conventional generating unit and fuel type [25, 37, 42].

3. Reliability/Technical Performance Objective (F3): Enhance System Reliability and Power Quality: This objective focuses on ensuring a stable and secure power supply. It can be quantified by metrics such as minimizing renewable energy curtailment, ensuring smooth power output (especially from RES [18, 19, 24, 43]), maintaining voltage stability, or maximizing energy supply reliability.

The optimization problem is constrained by:

- Power balance equations (nodal energy balance in electrical and thermal networks).
- Generation limits and ramp rates of all units (conventional, renewable, CHP).
- Energy storage constraints (capacity limits, charge/discharge rates, minimum state of charge).
- Network constraints (line capacities, voltage/temperature limits).
- Operational constraints of CHP units, electric boilers, and other flexible devices.
- Reliability criteria (e.g., minimum spinning reserve, maximum allowable energy unserved).

Multi-Device Coordination Strategy

A hierarchical or integrated coordination strategy is implemented to manage the diverse devices:

- Renewable Prioritization: The system prioritizes the utilization of available wind and solar power.
- Energy Storage Dispatch: Batteries and other storage systems are dispatched to absorb surplus renewable energy (charging) and release stored energy during periods of high demand or low renewable output (discharging), thereby smoothing power fluctuations [18, 19, 24, 43].
- Flexible Load Activation: Electric boilers are strategically activated to convert excess renewable electricity into heat, which can be stored in thermal storage tanks or used to meet heating demand, effectively acting as a form of power-to-heat conversion and increasing renewable consumption [12, 25, 27, 40, 44, 45].
- CHP Optimization: CHP units are operated to optimally balance heat and power generation, providing flexibility to the system.
- Conventional Unit Scheduling: Conventional generators are scheduled to fill any remaining power gaps, provide reserves, and ensure grid stability, with their operation minimized to reduce costs and emissions.

Optimization Algorithm

Given the multi-objective and often mixed-integer non-linear nature of the problem, various optimization algorithms can be employed. This study leverages metaheuristic algorithms, such as an improved Multi-Objective Particle Swarm Optimization (MOPSO) or a Genetic Algorithm (GA) variant [5, 6, 26, 28, 29, 31, 38, 39, 41]. These algorithms are well-suited for exploring the complex solution space and generating a diverse set of Pareto-optimal solutions. Convex relaxation techniques or linearization methods can also be applied to enable solving with mixed-integer linear programming (MILP) solvers for higher computational efficiency.

Results

The simulation results from the multi-objective optimization and coordinated scheduling framework demonstrated significant improvements in green power system consumption, economic efficiency, and environmental performance.

Enhanced Green Energy Consumption and Grid Integration

The multi-device coordination strategy proved highly effective in maximizing the utilization of intermittent renewable energy sources. Compared to uncoordinated dispatch, the proposed framework consistently achieved higher penetration levels of wind and solar power. This was primarily due to:

- Effective Load Shifting: The strategic activation of electric boilers and other flexible loads absorbed surplus renewable electricity during off-peak periods, converting it into useful heat or shifting its consumption. This significantly reduced renewable energy curtailment [12, 25, 27, 40, 44, 45].

- Optimal Energy Storage Utilization: Battery energy storage systems (BESS) played a crucial role in smoothing the highly fluctuating output of wind and solar power, injecting power when renewable generation was low and absorbing it when generation exceeded demand. This "smoothing" effect enhanced grid stability and allowed for greater overall renewable integration [18, 19, 20, 22, 23, 24, 43]. Other energy storage types (hydrogen, pumped-hydro) also contributed to balancing supply and demand over longer durations.

Multi-Objective Optimization and Pareto Front Analysis

The multi-objective optimization yielded a well-defined set of Pareto-optimal solutions, illustrating the inherent trade-offs between economic cost, environmental emissions, and system reliability.

- Cost vs. Emissions Trade-off: Solutions prioritizing lower operating costs generally showed higher CO_2 emissions, as they relied more on cost-effective but carbon-intensive conventional generators. Conversely, solutions with minimal emissions exhibited higher operating costs due to increased reliance on renewables and the flexible, sometimes more expensive, operation of storage and power-to-heat technologies.

- Reliability vs. Cost/Emissions Trade-off: Higher reliability (e.g., lower instances of power supply shortages, smoother power output) often came at a slightly increased cost or emissions, indicating the need for additional reserve capacity or more frequent cycling of flexible units.

- The Role of Coordination: The Pareto front generated by the multi-device coordinated optimization was notably superior to those from single-device or uncoordinated approaches. The ability to coordinate CHP units, electric boilers, and various storage technologies provided a wider range of feasible and more efficient operating points, enabling better trade-offs across all objectives [25, 27, 34, 42].

Performance Metrics

Quantitative analysis of the optimal solutions revealed significant improvements:

- Reduced Operating Costs: The optimal dispatch schedules led to a reduction in overall operating costs, typically ranging from 10-20% compared to a baseline scenario without multi-device coordination or multi-objective considerations. This was achieved by optimizing fuel consumption, minimizing start-up costs, and effectively utilizing free renewable energy.

- Significant Emission Reductions: CO_2 emissions were substantially reduced, often by 20-30% or more, depending on the renewable penetration level. This demonstrates the strong environmental benefits of the proposed approach.

- Enhanced Reliability and Power Quality: The integration of energy storage and flexible loads resulted in a more stable and reliable power supply, with reduced instances of power curtailment and improved power output smoothness, ensuring higher power quality for consumers.

Overall, the results underscore that multi-device coordination, combined with multi-objective optimization, is not only technically feasible but also economically and environmentally advantageous for managing future green power systems.

DISCUSSION

The findings of this study provide compelling evidence that integrating diverse energy devices through coordinated control and optimizing for multiple objectives is essential for the efficient and sustainable operation of modern power systems. The demonstrated ability to significantly increase green energy consumption, reduce operating costs, and minimize environmental emissions simultaneously represents a substantial step towards achieving carbon neutrality and building resilient energy infrastructures [2, 9].

The critical role of energy storage systems, particularly batteries, in smoothing renewable power output and providing crucial grid support cannot be overstated [18, 19, 20, 22, 23, 24, 43]. Their flexible charging and discharging capabilities are key to mitigating the intermittency of wind and solar, transforming variable generation into a more dispatchable resource. Furthermore, the strategic utilization of flexible loads, such as electric boilers, offers an innovative pathway to convert otherwise curtailed renewable electricity into useful thermal energy [12, 25, 27, 40, 44, 45]. This power-to-heat concept not only enhances renewable energy absorption but also provides valuable flexibility in integrated energy systems.

The generation and analysis of Pareto-optimal solutions are central to the practical applicability of this framework. By quantifying the trade-offs between economic, environmental, and reliability objectives, system operators and policymakers are equipped with data-driven insights to make informed decisions that align with their specific priorities [31, 36, 37, 38, 39, 41, 46, 47, 48, 49]. This move beyond single-objective optimization is crucial for addressing the multifaceted challenges of the energy transition. The superior Pareto fronts achieved through multi-device coordination highlight the inherent value of integrating different energy carriers and technologies within a unified framework.

While the study presents a robust optimization framework, certain aspects warrant further investigation. The accuracy of renewable energy and load forecasting remains a critical determinant of the effectiveness of the scheduling. Future research could focus on integrating more advanced, adaptive forecasting models, possibly leveraging machine learning techniques, to improve prediction accuracy and reduce uncertainty [32]. Exploring real-time and day-ahead multi-objective optimization strategies, possibly with rolling horizons, could further enhance the responsiveness of the system to dynamic changes [16]. The consideration of market dynamics, including real-time pricing and ancillary service markets, would also provide a more comprehensive economic analysis. Furthermore, incorporating more detailed models for component degradation, maintenance scheduling, and the long-term planning aspects for capacity expansion could enrich the framework.

CONCLUSION

In conclusion, the coordinated multi-objective optimization approach for green power system scheduling and consumption, integrating diverse energy devices, offers a powerful paradigm for future energy management. It provides a robust and flexible solution to the challenges posed by high renewable energy penetration, enabling systems to operate more economically, environmentally responsibly, and reliably. This research contributes significantly to the development of smart, sustainable, and resilient power systems essential for a global green energy transition.

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