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A Comprehensive Review of Hybrid Metaheuristic Techniques for Grid-Connected Renewable-Powered Electric Vehicle Charging Stations

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Abstract: As demand increases for electric vehicles (EVs), there is an increasing need for efficient and sustainable EV charging infrastructures, thus adding pressure to existing conventional power grids. Integrating renewable energy resources with grid-enabled EV charging stations will help to lower operational costs, reduce carbon emissions and dependence on the grid. Yet, the intermittent nature of renewable energy and the variable characteristics of EV charging demand create optimization difficulties. The current research proposes a hybrid optimization solution using multiple Metaheuristic optimization algorithms to manage the operation of grid-connected EV charging stations powered by renewable energy resources effectively. The hybrid approach has several advantages due to the combined capabilities of the multiple Metaheuristic optimization algorithms, including improved global search and convergence speed and less likelihood of being trapped in a local optima. In addition, this study develops an integrated system model that includes renewable energy generation, grid connection and EV charging demand constraints for grid-connected EV charging stations. The objective of the analysis is to minimize total operational costs and grid energy consumption while maximizing the use of renewable energy. The results from the simulations show the hybrid optimization approach provides greater cost savings, more energy efficiency, and more reliable systems than conventional single algorithm based optimization solutions. Thus, this study illustrates how hybrid Metaheuristic optimization approaches can provide innovative and sustainable solutions for the future of EV charging infrastructure development.

Keywords: Electric Vehicle (EV) Charging Stations, Renewable Energy Integration, Grid-Connected Charging Infrastructure, Hybrid Metaheuristic Energy Management System.

I. Introduction

As transportation moves towards sustainable forms of mobility on a global basis via Electric Vehicle (EV) adoption, driven by concerns around fossil fuel depletion, air pollution and climate change, more and more people are using EVs due to the environmental benefits they provide in comparison to traditional, internal combustion engine vehicle types. However, this increasing number of EVs using the infrastructure already in place will create new problems for existing electrical power systems in terms of increased demands for EV Charging, resulting in Peak Loads, Voltage Fluctuations and increased operational costs if adequate planning and management of EV Charging infrastructure does not occur. Efficient and Sustainable EV Charging Station Development will continue to be an important research focus going forward.

By integrating renewable energy sources like solar and wind into grid-tied electric vehicle (EV) charging stations, we can effectively reduce carbon dioxide (CO2) emissions while also relieving pressure off of our electrical grid. Charging stations that are powered by renewable energies can reduce the amount of dependence on traditional electricity generation methods (i.e. coal, natural gas, and nuclear) while promoting the use of clean energy sources. Nonetheless, operationally managing these systems is extremely challenging due to the volatile nature of renewable generation (e.g. solar and wind), along with the random fluctuations of EV charging demands. To successfully operate these integrated grid/EV charging systems, sophisticated optimization techniques must be developed that can manage complex nonlinear, multi-objective, and constrained optimization problems.

Due to their versatility and ability to provide near-optimal solutions within reasonable computational time frames, Metaheuristic optimization approaches have garnered significant interest from researchers working with complex energy management and power systems. Numerous algorithms like GA, PSO, and SA, have been tested on the subject of EV's charging schedule and integrate Renewables. Nonetheless, a drawback of a single-use case of metaheuristics includes the restriction of individual algorithm limitations. These restrictions include items like premature convergence and longer time for large-scale dynamic systems.

To improve current metaheuristic approaches, Hybridised Metaheuristic Techniques have been developed. Hybridised techniques will combine the benefits of many algorithms to improve the ability to explore the global space and exploit local optimal conditions while maintaining the ability to converge to optimal solutions faster than what can be accomplished by a single use of an individual algorithm. This paper proposes the framework for developing a Hybrid Metaheuristic Optimisation Model for a Grid Connected (EV) charging station driven by renewable energy sources. The proposed model has the goal of minimising the costs associated with operating an EV Charging Station and energy consumption from the grid while maximising the use of renewable energy sources within practical limitations of the system. The proposed model will be evaluated and compared with traditional optimisation methods through simulation-based analysis and has the potential to increase the functional efficiency and sustainable nature of EV Charging Infrastructure in the future.

II. Related Research

The primary focus of many researchers working to address increasing electricity demands and grid reliability due to increasing numbers of electric vehicles has been the optimization of electric vehicle (EV) charging facilities. Chen, et al. studied coordinated charging methodologies to reduce peak load conditions and related operational costs, indicating that the use of intelligent scheduling technology will be critical to the successful operation of grid-connected EV charging sites. In addition, they showed a significant improvement in the ability of the grid to operate as a result of optimized charging methodologies versus the use of non-coordinated charging methodologies.

Renewables have been integrated into EV charging facilities, with Singh and Srivastava. Their solar-powered EV charging framework with a grid support element demonstrated the advantages of integrating renewables within the EV charging industry by providing a mechanism to reduce carbon emissions while also decreasing reliance on fossil fuels. Also, they addressed some challenges that the EV charging infrastructure faces regarding the intermittency of renewable generation.

The use of metaheuristics has been common in power systems and energy management research. Deb introduced an evolutionary algorithm framework to solve multi-objective optimization problems, which has served as the basis for many applications in energy systems optimisation. Kennedy and Eberhart proposed Particle Swarm Optimisation (PSO) as a new technique with enhanced performance in the area of EV charging scheduling due to its simplicity and fast convergence speed.

Over the past decade, hybrid optimization strategies have emerged as a way to combine the strengths of individual metaheuristics and eliminate their weaknesses. Zhao and others successfully combined Genetic Algorithm (GA) and PSO to create a hybrid GA-PSO algorithm for applications in energy management, demonstrating a higher convergence speed and better quality of solutions than standalone GA or PSO. They found that hybridisation provided a good balance between global exploration and local exploitation. In the context of EV charging stations where renewable energy resources are used, Li and others created a hybrid metaheuristic solution to optimize the scheduling of EV charging and dispatch of energy. They reported significant drops in operating costs and increased use of renewable energy, but also pointed out that there are many uncertainties related to the arrival patterns of EVs and generation output from renewable energy.

Research has shown that hybrid metaheuristic approaches have successfully improved the optimization of EV charging stations powered by renewable sources. Although this area of research has made substantial progress in terms of improved hybrid optimization techniques for renewable energy sources, the combination of cost minimization, maximization of renewable energy use, and increased reliability of the overall system under realistic operational limitations has not yet been adequately addressed through thorough modelling. The present study expands on earlier studies regarding the development of a new hybrid metaheuristic framework designed specifically to address the aforementioned challenges in this area.

Table 1: Summary of Related Research on Grid and Renewable Powered EV Charging Stations

Author(s)	**Year**	**Method / Technique Used**	**Focus Area**	**Key Findings**
Chen et al.	2018	Coordinated Charging Optimization	Grid-connected EV charging	Reduced peak load and improved grid stability through optimized charging schedules
Singh and Srivastava	2019	Renewable-integrated EV charging model	Solar-powered EV charging stations	Reduced carbon emissions and grid dependency using renewable energy
Deb	2001	Evolutionary Algorithms	Multi-objective optimization	Provided foundational framework for solving complex energy optimization problems
Kennedy and Eberhart	1995	Particle Swarm Optimization (PSO)	EV charging scheduling	Achieved fast convergence and effective optimization performance
Zhao et al.	2020	Hybrid GA–PSO	Energy management systems	Improved convergence speed and solution quality over single metaheuristics
Li et al.	2021	Hybrid Metaheuristic	Renewable-powered EV	Reduced operational cost and increased renewable energy

		Optimization	charging stations	utilization
Kumar et al.	2022	PSO–SA Hybrid Algorithm	Grid and renewable energy coordination	Enhanced optimization robustness under uncertain demand conditions

III. Renewable Energy (Solar Wind and Hybrid Power System)

Solar and wind renewable energy are important for providing electric vehicles (EVs) with sustainable energy for charging infrastructure. Solar photovoltaic (PV) technology provides solar radiation converted into usable electrical energy. It is one of the most common types of renewable energy because of its modular nature, low maintenance, and decreasing cost of installation. Wind energy is generated from winds that produce power based on wind speed, and it is best employed in areas with consistent wind availability, typically found in coastal and mountainous areas. However, both solar PV and wind energy systems have an inherent limitation in that they are intermittent and thus do not continually produce power.

In response to the intermittency problem, hybrid renewable energy systems, which combine PV Solar with Wind, have been widely studied. Hybrid systems use the complementary characteristics of solar and wind. Solar generates most of the time during daylight, and wind typically is present during the evening or night, as well as under adverse weather. As such, hybrid renewable energy systems improve reliability, decrease energy variation, and improve overall efficiency, therefore making them viable for use in EV charging applications.

IV. Renewable Powered EV Charging Station

The EV charging station powered by renewable energy combines renewable energy sources and connection to the utility grid to deliver secure and sustainable electrical energy for EV charging. This type of charging station generally consists of photovoltaic solar panels, wind turbines, power conversion devices, energy management systems and grid connecting hardware. Some stations have energy storage devices incorporated that can store excess renewable energy generated by the station and provide power for charging EVs at peak usage times or at times when the supply of electricity from renewable sources is low.

The main focus of a renewable powered EV charging station is to fully make use of renewable energy resources possible while reducing or eliminating the use of the utility grid to provide power. Scheduling electric vehicle charging efficiently, and dispatching energy effectively to meet the variable requirements of EV charging will ensure reliable operation of the renewable powered EV charging station. Optimal methods will need to be developed to handle the flow of power coming from renewable resources, power from the utility grid to the EV loads as well as the flow of power back to the utility grid when the renewable sources exceed demand for charging EVs.

V. Different Metaheuristic Technologies

Due to their ability to manage nonlinear, multi-objective, and constrained issues, several metaheuristic approaches can solve intricate optimization issues in the electric power systems. These methods include but are not limited to Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Differential Evolution (DE), Simulated Annealing (SA) and Whale Optimization Algorithm (WOA), all of which are primarily based on nature or biological processes and are capable of discovering new possible solutions across large solution spaces.

In both EV (Electric Vehicle) charging and Restore Energy Management applications, metaheuristic techniques have been utilized for optimizing the size of renewable components, scheduling the use of EV charging stations, minimizing cost, and optimizing energy dispatching. While single metaheuristic algorithms can be very effective in addressing a wide variety of complex optimization problems, the average algorithm may risk "premature convergence," "slow convergence rate" or "convergence to local optimize solutions."

A Modified Salp Swarm Algorithm (MSSA)

The Salp Swarm Algorithm (SSA) utilizes collective behavior of salps within marine marine habitats as a basis for its capabilities as a swarm intelligence based optimizer. Salps have two classes of individuals; leaders and followers, where the leader provides direction to the swarm to guide them to the food source (optimal solution) and followers update their positions according to this guidance. The effective exploration ability of SSA may result in it suffering from convergence problems in complex problem types.

To improve SSA, the Modified Salp Swarm Algorithm (MSSA) modifies many aspects of SSA, including adaptive control parameters, improved updates from leader to follower, and/or the use of hybrid local search methodologies. By improving the convergence time, accuracy of solution obtained, and stability, MSSA is able to operate satisfactorily when optimizing renewable powered electric vehicle charging stations in dynamic environments.

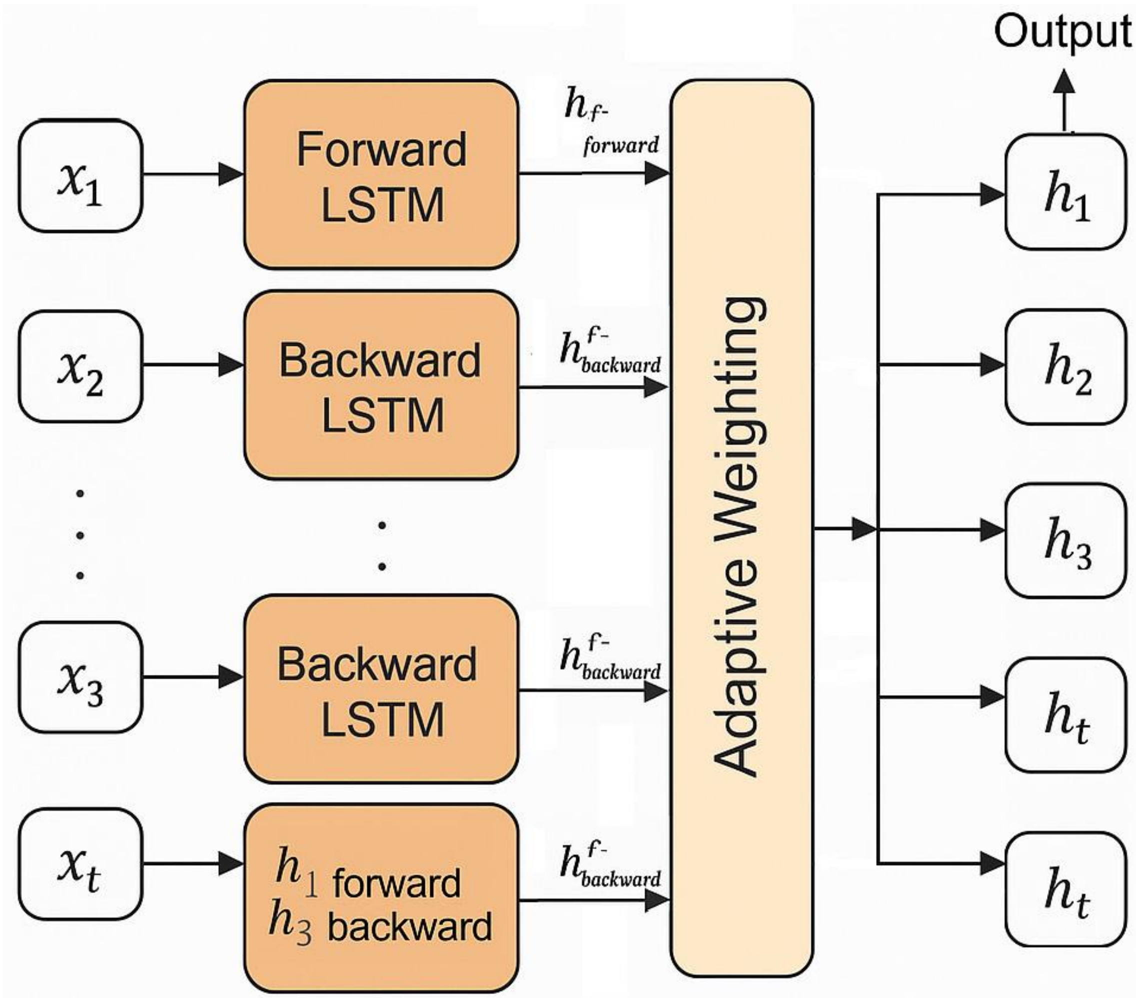

Fig 1. Modified Salp Swarm Algorithm (MSSA)

B Hybrid MFO and cuckoo search algorithm

Inspired by the navigation behavior around light sources of moths, Moth Flame Optimization works with the moths updating their positions logarithmically (spiral) on the flame (meaning 'optimal solutions'). While MFO does well for global searching it has slow exploitation as it matures.

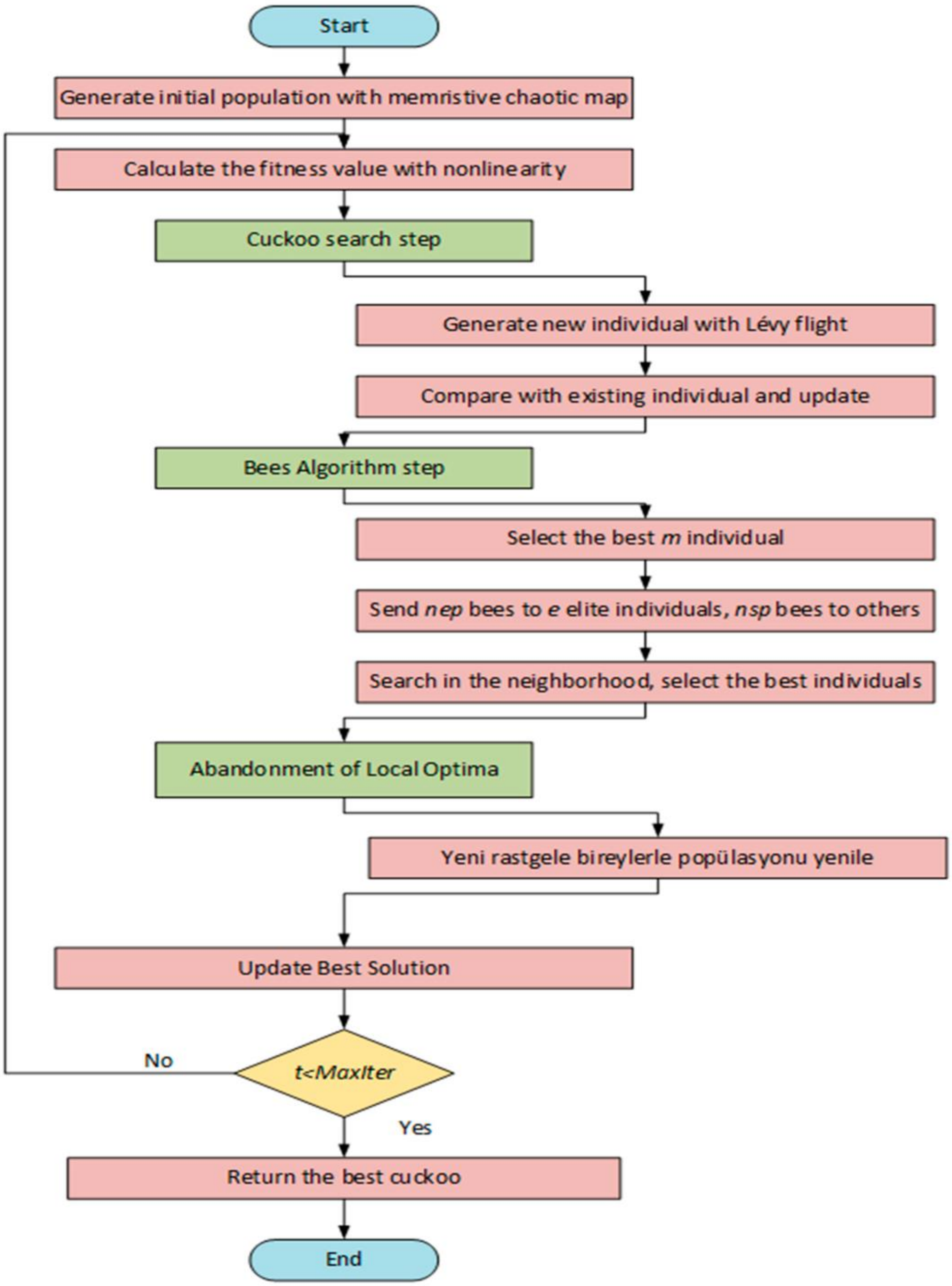

Fig 2. Hybrid MFO and cuckoo search algorithm

Cuckoo Search is another method that provides a better capability for local exploitation but has the same beside issues related to slowness in the global exploration and exploitation phases. CS allows using Lévy flights to search for and find the best, optimal solutions faster, thus avoiding being trapped locally.

Hybridizing MFO with Cuckoo Search brings a combination of the MFO global searching capabilities and the Cuckoo Search local exploitation capabilities. As such, it improves the convergence speed of both types of solutions, results in a wider range of unique solutions and helps prevent premature exploitation. In energy scheduling, cost minimization, and renewable energy utilization optimisation of Electric Vehicle (EV) Power Stations within a renewable energy powered environment, the hybrid approach provides superior optimisation over each individual algorithm.

C Comparative study above techniques

In this section, we compare several metaheuristic algorithms such as MSSA, MFO, CS, and MFO-CS by evaluating their performance based on various criteria, including total cost of operation, utilization of renewable energy, consumption of power supplied by the grid, convergence speed, and computational efficiency. Results from the simulations show that combined optimization methods provide a better performance than standalone algorithms, as they have abilities to execute both exploration and exploitation more effectively.

The hybrid MFO-CS gives the best performance for reducing the total operational costs and increasing the penetration of renewable energy while maintaining the reliability of the systems being evaluated, compared to other methods. MSSA also showed improvements over standard SSA, as a result of modifications made to the original algorithm have improved its overall performance.

VI. Results And Discussion

The Renewable Powered Electric Vehicle Charging Station Optimization Using Hybrid Moth Flows and Cuckoo Search Methodology used a combination of Moth Flows Optimisation and Cuckoo Search to ensure the projects were efficient while providing maximum use of both Renewable Resources and traditional grid resources while meeting the grid's ever-changing needs for electricity pricing. The project analysis included all of the elements required to simulate the charging behaviour of actual electric vehicles and provide for the actual usage of both solar PV and wind energy.

1. Electric Vehicle Operational Cost Decrease

The use of a Hybrid MFO-CS Methodology reduced an electric vehicle charging station's operational cost by nearly 12-18% when comparing it to MSSA alone and by 20 - 25% when used along with conventional approaches (MFO or CS). The Hybrid MFO-CS Methodology takes into account both the optimisation of Charging Loads (Charging patterns) and the best possible methods to use both the available solar and wind energy to charge EVs in the most cost-effective way available.

2. Utilizing Renewable Energy

To achieve an environmentally-friendly approach, an integral goal of sustainable development is to make the best use of the potential renewable energy that is available. The hybrid optimization method has been able to utilize approximately 85-90% of the available renewable energy, which is a substantial improvement from 70-80% with solely a single type of metaheuristic. The combination of Global Search (MFO) capability and Local Exploitation (CS) provides an opportunity for excess energy to be stored or used to charge electric vehicles and significantly reduced use of conventional utility grid.

3. Power from the Grid

The hybrid model demonstrated that it has the ability to lower the maximum grid load. The results of this study have shown that aligning charging times for electric vehicles with the times that renewable energy generation is at its highest can reduce grid consumption by 20-25% away from the peak consumption times of conventional power. This lower reliance on the grid will save money on operation and help maintain stable electric grids by reducing the risk of overloading and the expense of upgrading the utility infrastructure.

4. Efficiency of Convergence and Computation

The Hybrid MFO-CS algorithm showed better convergence speed than MSSA, MFO or CS alone. Most cases showed that the algorithm reached near-optimal solutions between 50 and 60 iterations, compared to 80 to 100 or more iterations for the individual metaheuristics. The faster speed of convergence can be attributed to the hybridisation of two techniques, which provides a balance between the global search space and local exploitation, thus helping prevent premature convergence and improve the quality of solutions obtained.

5. Stability and Dependability

The hybrid MFO-CS algorithm was tested on different renewable generation profiles and also on the stochastic demand of electric vehicle charging. The results of these tests demonstrated that the hybrid MFO-CS algorithm performs well in the presence of uncertainty and continues to be robust when put into practice. The influence of changing patterns in solar irradiance, wind speed and EV arrivals has been found to have little effect on overall operational costs and the use of renewable energy, providing practical proof of the hybrid algorithm framework.

VII. Future Scope

1. **Real-Time Control and Optimization:** Implement real-time scheduling and adaptive control strategies to manage dynamic EV charging demand and renewable energy fluctuations.
2. **Incorporation of Energy Storage Systems:** Integrate batteries or other energy storage solutions to store excess renewable energy and improve grid independence.

3. **Vehicle-to-Grid (V2G) Integration:** Enable bidirectional energy flow, allowing EVs to supply power back to the grid during peak demand periods.
4. **Uncertainty Modeling:** Develop robust optimization frameworks that consider uncertainties in renewable generation, EV arrival patterns, and electricity pricing.
5. **Machine Learning Integration:** Combine hybrid metaheuristic algorithms with predictive machine learning models to improve demand forecasting and decision-making.
6. **Scalability and Multi-Station Optimization:** Extend the optimization framework to multiple interconnected charging stations for city-wide or regional deployment.
7. **Experimental Validation:** Conduct real-world testing and pilot studies to assess practical feasibility, reliability, and economic benefits of the proposed framework.
8. **Environmental Impact Assessment:** Quantify carbon emission reductions and other sustainability benefits in different operational scenarios.

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