



## DYNAMIC COMBINED ECONOMIC EMISSION DISPATCH IN RENEWABLE ENERGY MICROGRIDS USING ZEBRA OPTIMIZATION ALGORITHM

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### ABSTRACT

The increasing demand for energy necessitates the implementation of sustainable solutions that incorporate renewable energy sources (RES), specifically solar and wind. Nevertheless, the inherent variability of renewable energy sources (RES) presents a challenge in the optimization of power dispatch, particularly in islanded microgrids. The Combined Economic Emission Dispatch (CEED) problem in a three-unit operational system under dynamic load demand conditions is the subject of this study. Four scenarios are taken into account for the operation of the system such as Thermal-only; Thermal + Wind; Thermal + PV; and Thermal + Wind + PV. In order to guarantee system reliability and reduce both generation cost and emissions, a weighted sum approach is implemented in conjunction with the Zebra Optimization Algorithm (ZOA). This work had done using the MATLAB 2020 software. The proposed method effectively manages constraints such as ramp rate limits and thermal unit operating boundaries, demonstrating enhanced efficiency and adaptability in comparison to traditional techniques.



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## I. INTRODUCTION

Power systems are tasked with the efficient management of energy production, transmission, and distribution to consumers. Given that energy demand has recently exceeded production capacity, existing power stations must be used to their maximum potential instead of constructing new facilities to accommodate the load. The economic load dispatch (ELD) model is the only model that accounts for load demand. This is the only model capable of ascertaining the distribution of power-generating units while conforming to constraints. The study [1] have used evolutionary algorithms to provide computer-aided solutions for the issues related to economic load dispatch. Despite the limitations given by the system, the objective is to generate the maximum feasible amount of electricity.

In [2] uses a combination of artificial intelligence and renewable energy distribution to optimize existing power networks for various applications. This enhancement may serve several purposes. In [3] they have developed a unique hybrid optimization technique that enhances energy efficiency and dispatch to address the issues related to the optimization of economic load dispatch. The paper [4] had examine the cost-reliability trade-off using sophisticated evolving intelligence algorithms developed for the integration of renewable energy sources. These algorithms were developed for research purposes. The multi-objective CEED problem leads to a decrease in both pollution emissions and fuel expenditures.

At Emission Dispatch, our primary objective is to decrease the volume of dangerous pollutants emitted by coal-fired power plants. The pollutants consist of carbon monoxide, sulfur dioxide, and nitrogen oxides. The study [5] developed an algorithm for real-coded chemical processes aimed at minimizing costs and emissions related to economic emission load dispatch. This was executed to attain the study's principal objective. In [6] they have conducted comprehensive ELD testing, revealing that search group optimization enhances convergence time and solution accuracy. These results underscore the significance of search group optimization. The study [7] had extend the idea to intelligent distribution networks, which oversee voltage stability and include virtual power plants fueled by renewable energy sources. Measures are implemented to fortify the power grid.

The adoption of ELD requires continuous dynamic demand integration to minimize costs, emissions, and grid instability. To ensure that power systems operate effectively and sustainably amidst varying load patterns, it is essential to use adaptable optimization strategies. The paper [8] enhanced grid stability with the use of real-time economic load dispatch and renewable energy curtailment. This was achieved despite the fairly complex nature of the data processing operation. Despite incurring substantial processing costs, Dragonfly successfully enhanced the accuracy of probabilistic ELD [9]. Despite considering parameter sensitivity, [10] successfully optimized the thermal-wind economic load dispatch using chaotic sine cosine. The study [11] enhanced ELD convergence by artificial ecosystem optimization. This was achieved despite requiring substantial processing effort. To address the coal problem, one should integrate wind power plants with coal-fired thermal power facilities. This technique maximizes sustainability, cost-effectiveness, and pollution reduction to their fullest potential.

The grid's enhanced resilience has led to an increased need for optimization frameworks proficient in managing unpredictability and dynamic load distribution. It is regrettable that [12] could not successfully augment their research, despite their efforts to enhance short-term hydrothermal dispatch to boost production. In paper [13] successfully used ELD with multi-fuel thermal and renewable energy sources, leveraging the Equilibrium Optimizer. This enabled him to save costs by adjusting the ELD parameters to get the intended outcome. This was implemented to achieve the goal of minimizing expenditures to the greatest extent feasible. The study [14] introduced new avenues of research in their study on renewable-integrated ELD optimization methodologies; nevertheless, they failed to test the scalability of their approaches prior to advancing their work. The use of photovoltaics in economic load dispatch seeks to reduce fossil fuel consumption, operational costs, and environmental impact.

Due to the unpredictability of the power source, optimization enhancements are necessary for photovoltaic (PV) output. These modifications are essential to guarantee the stability of the grid, the efficiency of the power distribution system, and the economic viability of the system amid variable load conditions. Although challenging to quantify, optimization strategies for CEED, whether using PV and wind or not, are successful, as shown in [15]. Despite the challenges in calculating them, some tactics prove effective. The study [16] discovered that solar sharing via PSO was both cost-effective and environmentally beneficial. Despite solar electricity being an intermittent energy source, this was the circumstance. In [17] endeavored to enhance the precision of their predictions by including photovoltaic and transmission losses into economic emission dispatch (EED). This was undertaken to enhance the precision of their forecasts. Solar and wind energy exemplify renewable energy sources that enhance the efficiency of electric vehicles (EVs), decrease fuel costs, promote sustainability, and mitigate pollution.

Due to the sporadic characteristics of renewable energy sources, the use of sophisticated optimization and energy storage technologies is essential for sustaining grid stability. Despite their complexity, hybrid systems are more economical and enhance energy security. Hybrid systems also reduce costs. In the study [18] devised a metaheuristic algorithm inspired by bats to enhance resource use efficiency. This idea addresses the fundamental difficulty associated with renewable energy. Due to the unpredictability of renewable resources, [19] assert that probabilistic modeling was used to account for this factor. The study [20] enhanced the efficiency of the task by analyzing CEED optimization approaches that included photovoltaic and wind generation systems. In [21] they have used an advanced pyrotechnics algorithm to optimize the combined dispatch of renewable energy sources. The intricacy of scheduling is further exacerbated by the use of solar and wind power prediction models, as shown in [22].

The study [23] are doing research on the integration of wind, solar, and hydropower to develop a more dependable hybrid dispatching system. Following an analysis of the system's cost and performance, [24] conclude their study on the financial implications of incorporating solar energy into the existing power grid. In [25] maximize CEED amidst fluctuating energy supply by using sophisticated hybrid algorithms, while simultaneously managing costs, emissions, and grid stability. This enables them to get effective optimization. To effectively integrate intermittent renewable energy sources such as solar, thermal, and wind power into Economic Load Dispatch (ELD), rigorous optimization is essential. The Zebra Optimization Algorithm (ZOA) effectively addresses multi-objective constraints, enabling it to enhance grid stability, decrease generation costs, and minimize emissions. Consequently, it can achieve these aims. Ultimately, it will provide optimal dispatch solutions, hence enhancing the endurance of hybrid power networks. This is now achievable due to its adaptive search capabilities.

## II. PROBLEM FORMULATION

By superimposing the input-output properties of the boiler-turbine-generator system, the fuel cost function [25] is usually expressed as:

$$F_{C_{Total}} = \sum_{i=1}^N f_i(P_{gi}) = \sum_{i=1}^N (a_i + b_i P_{gi} + c_i P_{gi}^2) \quad \$/hr \quad (1)$$

By integrating the NO<sub>x</sub>, SO<sub>x</sub>, and CO<sub>x</sub> emissions of a thermal power plant, the entire emission function [25] is depicted as:

$$E_T = \sum_{i=1}^N f_i(P_{gi}) = \sum_{i=1}^N (\alpha_i + \beta_i P_{gi} + \gamma_i P_{gi}^2) \quad kg/hr \quad (2)$$

Constructing a single objective function that concurrently achieve both goals is inequitable, since reducing emissions and decreasing gasoline costs may be inherently contradictory. This is due to the potential incompatibility of these two objectives. The Combined Economic Emission Dispatch (CEED) function may be articulated as follows [25]. The aim is achieved by integrating the Weighted Sum and Price Penalty Factor (PPF) techniques.

$$CEED_T = W * F_{C_{Total}} + (1 - W) * h * E_T \quad (3)$$

The PPF is employed to transform emissions into a cost equivalent value.

$$h_i = \frac{F_C(P_{gi,min})}{E_T(P_{gi,max})} \quad (4)$$

Incorporating RES like solar and wind power into the ELD problem requires that the system adhere to inequality constraints and stability constraints [25] to maintain power balance and equilibrium.

### II.1 EQUALITY CONSTRAINTS

$$\sum_{i=1}^{NG} P_{gi} + \sum_{i=1}^M W_{gi} + \sum_{i=1}^S PV_{gi} = P_{Demand} + P_{loss} \quad (5)$$

### II.2 INEQUALITY CONSTRAINTS

$$P_{gi,min} \leq P_{gi} \leq P_{gi,max} \quad (6)$$

$$0 \leq W_{gi} \leq W_{r_{gi}} \quad (7)$$

$$0 \leq PV_{gi} \leq PV_{r_{gi}} \quad (8)$$

## III. PROPOSED OPTIMIZATION ALGORITHM

### III.1 ZEBRA OPTIMIZATION ALGORITHM

The study [26] developed a metaheuristic inspired by the natural behaviours of zebras in herding, migration, and survival. This metaheuristic is inspired by the natural strategies used by zebras. The approach is referred known as the Zebra Optimization Algorithm (ZOA). The ZOA is intended to replicate the balance that zebras maintain between foraging for food in uncharted territories and evading hazardous environments. It is particularly adept at addressing multi-objective optimization challenges, shown by the Combined Economic Emission Dispatch (CEED) in hybrid power systems, a topic for which it was specifically developed.

**Population Initialization:** Generate an initial population of  $n$  zebras (candidate solutions):

$$X_i^0 = lb + rand(1, D) \cdot (ub - lb) \quad for \ i = 1, 2, \dots, n \quad (9)$$

**Fitness Evaluation:** Evaluate each zebra's fitness using the CEED objective function

$$fit_i = CEED_T(X_i) \quad (10)$$

**Global Best Update:** Update global best  $P_Z$  if a better fitness is found

$$P_Z^t = argmin(fit_i^t) \quad (11)$$

**Phase 1 – Foraging Behaviour (Exploration):** Zebra moves toward the best-known position

$$X_i^{t+1} = X_i^t + r \cdot (P_Z^t - I \cdot X_i^t) \quad (12)$$

If new position yields better fitness, update:

$$If \ f(X_i^{t+1}) < f(X_i^t) \Rightarrow X_i^t = X_i^{t+1} \quad (13)$$

**Phase 2 – Predator Avoidance Behaviour (Exploitation):** Strategy 1 (Lion Attack – Escape Strategy), Zebra escapes with random disturbance decreasing over time:

$$X_i^{t+1} = X_i^t + R \cdot (2r - 1) \cdot \left(1 - \frac{t}{t_{max}}\right) \cdot X_i^t \quad (14)$$

Strategy 2 (Other Predators – Defensive Strategy): Move based on interaction with randomly selected zebra  $AZ$

$$X_i^{t+1} = X_i^t + r \cdot (AZ - I \cdot X_i^t) \quad (15)$$

**Boundary Handling:** Ensure that the updated position remains within bounds

$$X_i^{t+1} = \min(\max(X_i^t + 1, lb), ub) \tag{16}$$

**Convergence Check:** Repeat steps until the stopping criterion is met

$$t = t + 1, \text{ stop if } t \geq t_{max} \text{ or convergence achieved}$$

**III.2 STEPS FOR ZOA-BASED CEED OPTIMIZATION**

1. **Problem Definition:** Define the CEED objective function incorporating generation cost, emission levels, and system constraints.
2. **Population Initialization:** Generate initial zebra positions representing candidate power dispatch solutions.
3. **Fitness Evaluation:** Evaluate each zebra's fitness based on economic cost, emission output, and constraint satisfaction.
4. **Exploration & Exploitation:** Use ZOA's dynamic movement strategy to explore new solutions or exploit known good regions, guided by the global best and peer interaction.
5. **Constraint Enforcement:** Apply generator output limits, ramp rate limits, and power balance conditions to maintain feasible solutions.
6. **Best Solution Update:** Track and update the best-performing solution after each iteration.
7. **Convergence Criterion:** Repeat the process until the termination condition is met (e.g., max iterations or acceptable error level).
8. **Result Analysis:** Analyze the optimized dispatch results to determine the most cost-effective and environmentally efficient strategy.

**IV. RESULTS AND DISCUSSIONS**

This paper addresses the Combined Economic and Emission Dispatch (CEED) problem for a three-unit thermal power system under diverse integration scenarios of renewable energy sources. The system parameters, renewable generation profiles, and load demand are derived from [25]. The CEED objective function is constructed as a weighted sum of fuel costs and emission levels. The Zebra Optimization Algorithm (ZOA) is executed in MATLAB 2020 to address the dispatch problem in four scenarios: (i) thermal-only, (ii) thermal + PV, (iii) thermal + wind, and (iv) thermal + PV + wind. The outcomes are juxtaposed with benchmark solutions found in the current literature to authenticate the performance and effectiveness of ZOA. The ZOA model parameters are:  $R=0.1$  (escape step size),  $r1$  and  $r2 \in [0,1]$ , and a dynamic equilibrium between exploration and exploitation based on iteration progress.

**IV.1 CASE STUDY 1: EXCLUSIVE THERMAL UNITS**

The CEED issue is addressed using the ZOA, focusing just on three thermal power units without including renewable energy sources. The aim is to reduce fuel expenses and pollution levels within a 24-hour timeframe, while maintaining power equilibrium and complying with operating restrictions. The system load requirement fluctuates between 140 MW and 250 MW during the day. According to the ideal dispatch plan established by ZOA, Unit 1 (Pg1) regularly functions at 37 MW, whereas Unit 3 (Pg3) sustains a stable output of 50 MW, suggesting that technical or economic considerations favour stationary operation. Unit 2 (Pg2) modulates its output between 53 MW and 160 MW, contingent upon the system's real-time load demands.

This guarantees a balanced alignment of supply and demand over the scheduling period. The optimization findings indicate a total fuel cost of 170,476 \$/hr and an emission level of 3,711.05 kg per hour. The total CEED cost for the 24-hour period is 151,475 \$/hr. The hourly CEED cost varies with demand, from a minimum of 5,395.10 \$/hr during low-demand times to a high of 7,116.70 \$/hr during peak load. These findings validate the efficacy of ZOA in addressing multi-objective optimization for thermal-only systems and provide a benchmark for evaluating enhancements from renewable integration in future scenarios.

Table 1: Hourly Optimal Results by ZOA for Case 1 (Thermal Only).

Hour	P1 (MW)	P2 (MW)	P3 (MW)	P-Thermal (MW)	Fuel-Cost (\$/hr)	Emission (Kg/hr)	CEED (\$/hr)
1	37	53	50	140	6051.1	112.85	<b>5395.1</b>
2	37	63	50	150	6256.2	116.13	5571.1
3	37	67.999	50	155	6359	118.37	5661.4
4	37	72.999	50	160	6461.9	121.01	5753.3
5	37	77.999	50	165	6565	124.05	5846.8
6	37	82.997	50	170	6668.2	127.49	5941.9
7	37	88	50	175	6771.6	131.33	6038.5
8	37	92.998	50	180	6875.1	135.57	6136.7
9	37	123	50	210	7499.3	169.41	6758.8
10	37	143	50	230	7918.5	199.97	6988.5
11	37	153	50	240	8128.9	217.64	<b>7116.7</b>
12	37	160	50	250	8340.1	229.45	7258.1
13	37	153	50	240	8128.9	217.65	<b>7116.7</b>
14	37	133	50	220	7708.6	183.89	6868.7
15	37	113	50	200	7290.6	156.53	6545.1

16	37	92.999	50	180	6875.1	135.57	6136.7
17	37	83	50	170	6668.2	127.49	5941.9
18	37	98	50	185	6978.7	140.21	6236.4
19	37	113	50	200	7290.6	156.53	6545.1
20	37	153	50	240	8128.9	217.64	<b>7116.7</b>
21	37	138	50	225	7813.5	191.72	6927.4
22	37	103	50	190	7082.5	145.25	6337.7
23	37	72.997	50	160	6461.9	121.01	5753.4
24	37	57.999	50	145	6153.6	114.29	5482.3
<b>Total</b>					<b>170476</b>	<b>3711.05</b>	<b>151475</b>

Source: Authors, (2026).

In Case 1, the whole demand for 24 hours is fully satisfied by thermal units, without any input from renewable sources. The thermal power production precisely corresponds to the hourly demand. In the first hour, the demand is 140 MW, entirely met by PT at 140 MW. At hour 10, demand reaches its zenith at 230 MW, with thermal generation precisely aligning at 230 MW. During peak demand hours, namely hour 12 (250 MW) and hour 20 (240 MW), the whole load is managed only by thermal plants, devoid of any renewable support. This configuration exemplifies the most conventional operation, yielding the greatest fuel expenses and emissions across all scenarios owing to exclusive dependence on fossil fuel-based generating. The whole power balance situation is shown in Table 6.

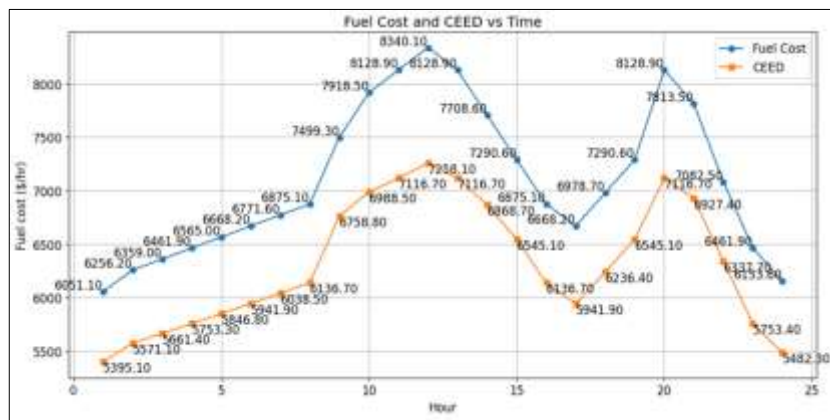


Figure 1: Hourly Variation of Fuel Cost and CEED – Case 1.

Source: Authors, (2026).

Figure 1 depicts the hourly fluctuations of Fuel Cost and CEED (Cost of Energy and Emission Dispatch) across a 24-hour duration. The horizontal axis indicates time in hours (1–24), and the vertical axis signifies fuel expense in \$/hr. The blue curve represents Fuel Cost, whereas the orange curve illustrates CEED. Both measures have a same trajectory, with values rising throughout the morning hours and culminating at Hour 11, when Fuel Cost attains a high of \$8340.10 and CEED nears \$7298.10. Subsequent to this apex, both curves exhibit a slow descent, followed by a secondary ascent at Hour 21, signifying another operational high. The proximity of the two curves indicates a robust link between fuel use and emission-related expenses. Every data point on the graph is labelled for clarity, offering comprehensive insight into the fluctuations in operational costs throughout the day.

#### IV.2 CASE STUDY 2: THERMAL + PHOTOVOLTAIC(PV) SYSTEM

In Case 2, a 40 MW photovoltaic (PV) system is included into the power grid in conjunction with the three existing thermal units. The PV source, deemed non-dispatchable and devoid of emissions, functions with a stable generation profile that directly mitigates a portion of the overall system demand. This integration significantly decreases the net load on thermal generators, so alleviating their operating strain and enhancing overall system efficiency. The ZOA is used to address the modified CEED issue in accordance with the altered load profile. Following the integration of PV power, the thermal units Pg1 and Pg3 maintain their base load outputs of 37 MW and 50 MW, respectively, while Pg2 modulates its output to align with the residual demand.

The optimum dispatch plan embodies this tendency, allowing the system to sustain viability amid fluctuating demand levels. Significant reductions are achieved in both economic and environmental parameters relative to Case 1. The aggregate fuel expenditure diminishes to \$166,659.86 per hour, emissions decline to 3,656.245 kg per hour, and the optimal CEED value is lowered to \$148,343.14 per hour. The findings underscore the substantial benefits of integrating solar energy into traditional thermal systems, illustrating ZOA’s efficacy in reducing costs and emissions in hybrid power systems. The incorporation of a 40 MW photovoltaic system in Case 2 alleviates the need on thermal production, particularly during daylight hours.

At hour 8, with demand at 180 MW, photovoltaic (PV) systems provide 16.18 MW, reducing the thermal load to 163.82 MW. At hour 10, photovoltaic (PV) systems reach their maximum production of 39.37 MW against a demand of 230 MW, hence decreasing thermal generation to 190.63 MW. In hour 13, photovoltaic (PV) production provides 31.94 MW, whereas thermal output has reduced to 208.06 MW, as seen in Table 6. During the early or late hours when sunshine is absent (e.g., hour 1 and hour 24), photovoltaic production ceases, and heat generation only fulfils the requirement. This partial integration mitigates fuel use and emissions during peak solar hours, hence improving overall efficiency.

Table 2: Hourly Optimal Results by ZOA for Case 2 (Thermal+PV).

Hour	P1 (MW)	P2 (MW)	P3 (MW)	P-Thermal (MW)	Fuel-Cost (\$/hr)	Emission (Kg/hr)	CEED (\$/hr)
1	37	53	50	140	6051.145	119.846	5395.138
2	37.0001	62.9991	50.0008	150	6256.2266	123.1261	5571.1
3	37	67.9995	50.0005	155	6358.991	125.366	5661.432
4	37	72.9994	50.0006	160	6461.9061	128.006	5753.338
5	37.0001	77.9998	50	165	6564.9701	131.0458	5846.809
6	37.0002	82.9698	50	169.97	6667.5654	134.4639	5941.279
7	37.0001	81.729	50.001	168.73	6641.956	133.5742	5917.569
8	37.0001	76.8197	50.0002	163.82	6540.6336	130.2924	5824.609
9	37.0002	98.9452	50.0046	185.95	6998.4514	148.131	6255.565
10	37.0004	103.625	50.0043	190.63	7095.6439	152.907	6350.636
11	37.0001	145.589	50.0007	232.59	7972.9227	211.3907	7020.94
12	37.0001	159.349	50.0005	246.35	8262.9119	236.7025	7201.801
13	37.0001	121.059	50.0004	208.06	7458.7749	173.7816	6716.816
14	37	106.186	50.0035	193.19	7148.8634	155.6689	6403.223
15	37.0004	102.918	50.0013	189.92	7080.8852	152.161	6336.111
16	37.0002	87.6995	50.0003	174.7	6765.3445	138.084	6032.63
17	37.0001	73.4279	50.0021	160.43	6470.7667	128.2518	5761.323
18	37.0002	95.6898	50	182.69	6930.8182	145.0124	6190.13
19	37.0002	112.999	50.0002	200	7290.6254	163.5255	6545.106
20	37.0002	152.999	50	240	8128.945	224.6456	7116.678
21	37	137.999	50.0008	225	7813.4513	198.7251	6927.431
22	37	102.999	50.0002	190	7082.5453	152.2459	6337.742
23	37.0001	72.9996	50.0004	160	6461.9057	128.006	5753.336
24	37	57.9998	50.0002	145	6153.6104	121.2861	5482.333
<b>Total</b>					<b>166659.859</b>	<b>3656.245</b>	<b>148343.1</b>

Source: Authors, (2026).

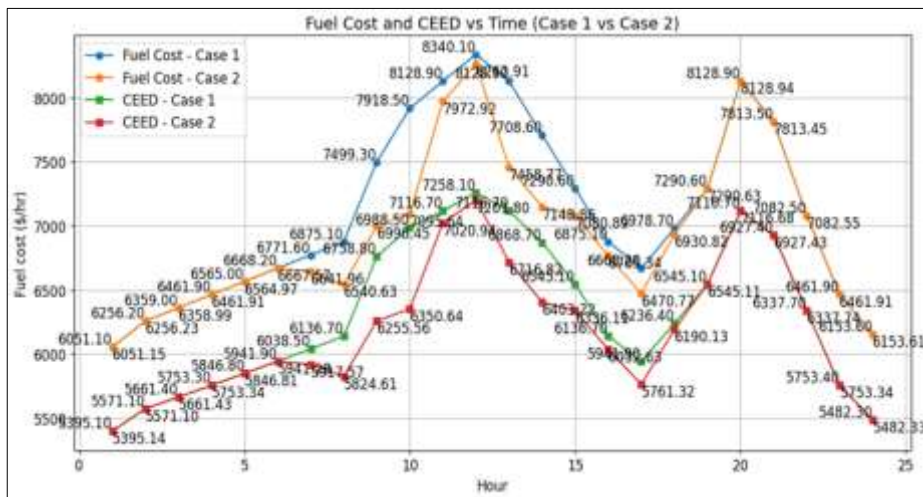


Figure 2: Hourly Variation of Fuel Cost and CEED – Case 1 and Case 2.

Source: Authors, (2026).

Figure 2 depicts the hourly fluctuations of Fuel Cost and CEED (Combined Economic and Emission Dispatch) for Case 1 and Case 2 across a 24-hour duration. The x-axis denotes the hours of the day, whilst the y-axis signifies the associated expenditures in \$/hr. The graph delineates four curves: Fuel Cost-Case 1, Fuel Cost-Case 2, CEED-Case 1 and CEED-Case 2. Overall, Case 2 demonstrates elevated fuel expenses compared to Case 1 at peak demand intervals, particularly between hours 10–13 and 20–21, indicating a heightened operational strain. Nonetheless, the CEED values in Case 2 are decreased at certain hours, indicating a successful decrease in emissions or enhanced incorporation of cleaner energy sources such as solar (PV) systems. The fuel cost and CEED trends reach their zenith at Hour 11, signifying a pivotal period for operational planning. Case 2 illustrates an enhanced balance between economic dispatch and environmental consequences.

### IV.3 CASE STUDY 3: THERMAL + WIND SYSTEM

In Case 3, a 30 MW wind power plant is incorporated into the existing thermal generating infrastructure. Similar to PV energy, wind power is a clean, non-dispatchable source; but, its intrinsically stochastic characteristics inject more unpredictability into the dispatch strategy. The CEED issue has been revised to include the dynamic wind profile, and the ZOA is used to ascertain the ideal generating schedule. The dispatch findings, as shown in Table 3, indicate that thermal units adjust to the fluctuations of wind power. Unit Pg1 operates consistently at its baseline of 37 MW, enhancing system stability. Pg3 functions consistently, while Pg2 adopts a flexible approach, modulating its output according to variations in wind availability. This architecture allows the system to effectively balance demand despite the unpredictability of renewable inputs.

In contrast to the other situations, Case 3 attains a total fuel cost of \$166,041.9 per hour and emissions of 3,612.80 kg per hour, culminating in a CEED value of \$147,886.74 per hour. The cost decrease in the PV-integrated scenario (instance 2) is minimal; nonetheless, this instance demonstrates increased fluctuation in emissions owing to the intermittent characteristics of wind energy. Nevertheless, the findings affirm that the incorporation of wind power improves both economic and environmental conditions compared to the thermal-only baseline. This scenario further illustrates ZOA's flexibility in controlling dispatch under uncertainty, showcasing its resilience in hybrid systems with dynamic renewable production.

Table 3: Hourly Optimal Results by ZEBRA Algorithm for Case 3 (Thermal+Wind).

Hour	P1 (MW)	P2 (MW)	P3 (MW)	P-Thermal (MW)	Fuel-Cost (\$/hr)	Emission (Kg/hr)	CEED (\$/hr)
1	37	51.2999	50	138.3	6016.341	117.4475	5365.85
2	37	54.4999	50.0001	141.5	6081.869	118.236	5421.132
3	37	58.7292	50.0008	145.73	6168.584	119.5299	5495.198
4	37	56.34	50	143.34	6119.575	118.7635	5453.209
5	37.0001	70.779	50.0009	157.78	6416.194	124.7845	5712.34
6	37.0001	78.0885	50.0014	165.09	6566.829	129.1043	5848.514
7	37	73.34	50	160.34	6468.909	126.2	5759.641
8	37.0001	67.4395	50.0005	154.44	6347.474	123.0952	5651.237
9	37	102.419	50.0003	189.42	7070.495	149.6407	6325.908
10	37	125.146	50.0038	212.15	7544.256	177.3812	6781.639
11	37.0001	140.199	50.0005	227.2	7859.639	200.3016	6954.016
12	37.0002	144.348	50.001	231.35	7946.846	207.2579	7005.336
13	37.0002	138.649	50.0003	225.65	7827.094	197.7738	6935.233
14	37	122.649	50.001	209.65	7491.993	173.9274	6751.173
15	37.0002	104.739	50.0002	191.74	7118.708	152.0933	6373.371
16	37.0001	79.2882	50.0018	166.29	6591.588	129.8951	5871.19
17	37.0001	79.5593	50.0007	166.56	6597.158	130.0763	5876.298
18	37	96.1297	50.0003	183.13	6939.942	143.4237	6198.922
19	37.0001	112.249	50.0007	199.25	7274.999	160.6239	6529.338
20	37.0001	152.829	50.001	239.83	8125.363	222.3307	7114.45
21	37.0003	137.847	50.0021	224.85	7810.305	196.4822	6925.656
22	37.0002	102.689	50.0007	189.69	7076.105	149.9213	6331.415
23	37.0001	71.9299	50	158.93	6439.869	125.4073	5733.535
24	37.0001	57.4195	50.0005	144.42	6141.717	119.0986	5472.14
<b>Total</b>					<b>166041.9</b>	<b>3612.796</b>	<b>147886.7</b>

Source: Aurthors, (2026).

Case 3 presents a 30 MW wind power system, yielding fluctuating but significant contributions that mitigate heat production. During the third hour, wind generation yields 9.27 MW in response to a demand of 155 MW, resulting in a reduction of PT to 145.73 MW. During windy periods, namely during hour 8, wind generation reaches a high of 25.56 MW, while power transmission decreases to 154.44 MW to meet a demand of 180 MW. During hour 9, wind generates 20.58 MW, while thermal provides 189.42 MW to satisfy the 210 MW demand. Despite fluctuations in wind power, which decreases to only 0.17 MW during hour 20, it continuously contributes to diminishing thermal dependence over many hours, as seen in Table 6. This scenario underscores the unpredictability of wind while illustrating how its incorporation might result in significant savings in thermal dispatch.

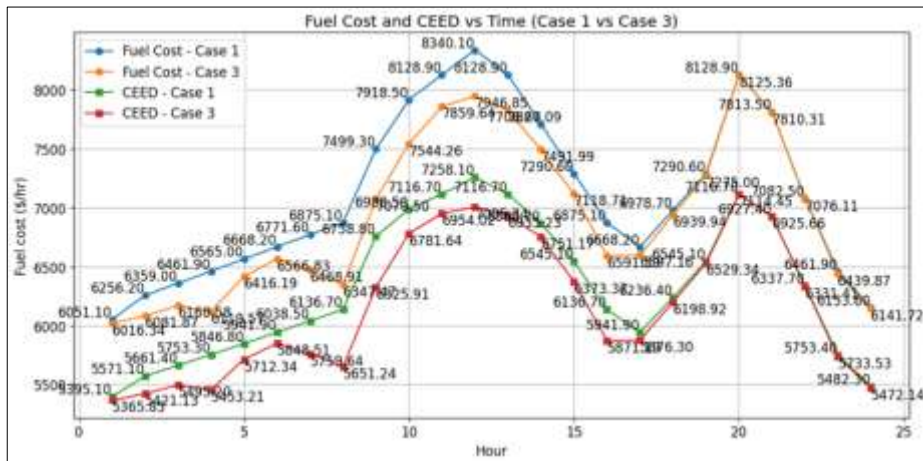


Figure 3: Hourly Variation of Fuel Cost and CEED – Case 1 and Case 3.

Source: Authors, (2026).

Figure 3 illustrates the hourly fluctuations of Fuel Cost and CEED (Combined Economic Emission Dispatch) for Case 1 and Case 3 during a 24-hour period. The study utilizes the Zebra Optimization Algorithm (ZOA), which proficiently optimizes both cost and emissions in dynamic load scenarios. In Case 1, which depends only on conventional thermal units, both fuel costs and CEED show steady increases during peak demand hours, peaking in the 11th hour when fuel costs approximate \$8128.90/hr and CEED nears \$7895.69/hr. This situation indicates elevated operating expenses and environmental repercussions resulting from the lack of renewable energy sources.

In contrast, Case 3 includes wind power production, resulting in substantial improvements in system performance. Despite the gasoline cost in Case 3 seeing significant peaks (particularly reaching 8340.10 \$/hr), the CEED values remain lower and more steady than those in Case 1. This illustrates that the incorporation of wind power mitigates emission-related expenses, despite potential temporary increases in fuel prices resulting from fluctuations in wind availability or supplementary thermal assistance. Figure 3 illustrates that the ZOA-based solution with wind integration in Case 3 attains superior environmental and economic equilibrium relative to the traditional configuration in Case 1. The findings highlight the benefits of hybrid renewable systems and sophisticated optimization methods in reducing total dispatch costs and emissions.

**IV.4 CASE STUDY 4: THERMAL + PV + WIND SYSTEM**

Case 4 incorporates 40 MW of PV and 30 MW of WP into the generating mix, mimicking a system mostly powered by renewable energy. This hybrid configuration significantly decreases the net burden on thermal generators, enabling a more environmentally friendly and economical dispatch approach. Table 4 illustrates that, with Pg1 and Pg3 fixed at 37 MW and 50 MW respectively, the ZOA dynamically modifies Pg2 to equilibrate the fluctuating net demand resulting from the integrated renewable profiles. This cooperation facilitates the more effective usage of thermal units. The system attains a minimum CEED value of ₹144,486.40 per hour, with a fuel expenditure of ₹162,242.50 per hour and a reduced emission cost of ₹3,571.30 per hour. Of the four scenarios, this hybrid integration provides the most significant improvement in both economic and environmental goals. These findings illustrate ZOA's resilience in managing intricate, uncertainty-driven dispatch situations and underscore the promise of synchronized renewable energy integration in forthcoming power systems.

Case 4 exemplifies a comprehensive hybrid system, using 40 MW of photovoltaic energy and 30 MW of wind power in conjunction with thermal generating. This yields the most efficient power dispatch configuration. In hour 10, the total renewable energy (PV: 39.37 MW, Wind: 17.85 MW) provides 57.22 MW of a 230 MW demand, enabling PT to decrease to 172.78 MW. During hour 13, photovoltaic systems generate 31.94 MW and wind energy contributes 14.35 MW, resulting in a total of 46.29 MW, therefore allocating 193.71 MW for thermal units. Even during the early hours, such as hour 3, the wind production of 9.27 MW supplements the thermal output of 145.73 MW to satisfy the 155 MW requirement shown in Table 6. This scenario illustrates the most effective power equilibrium, reducing fuel consumption and emissions while satisfying the same demand via optimum renewable resource deployment over a 24-hour period.

Table 4: Hourly Optimal Results by ZEBRA Algorithm for Case 4 (Thermal+PV+Wind).

Hour	P1 (MW)	P2 (MW)	P3 (MW)	P-Thermal (MW)	Fuel-Cost (\$/hr)	Emission (Kg/hr)	CEED (\$/hr)
1	37	51.3	50	138.3	6016.3	123.45	5365.9
2	37	54.5	50	141.5	6081.9	124.24	5421.1
3	37	58.73	50	145.73	6168.6	125.53	5495.2
4	37	56.34	50	143.34	6119.6	124.76	5453.2
5	37	70.779	50.001	157.78	6416.2	130.78	5712.3
6	37	78.059	50.001	165.06	6566.2	135.08	5847.9
7	37	67.066	50.004	154.07	6339.9	128.92	5644.5
8	37	51.26	50	138.26	6015.5	123.44	5365.2
9	37	78.37	50	165.37	6572.6	135.29	5853.8
10	37	85.78	50	172.78	6725.6	140.57	5995.4
11	37	132.79	50.001	219.79	7704.2	194.56	6866.3
12	37.001	140.7	50	227.7	7870.1	207.12	6960.1
13	37	106.71	50	193.71	7159.7	160.24	6413.9
14	37	95.838	50.002	182.84	6933.9	149.15	6193.1
15	37	94.659	50.001	181.66	6909.5	148.06	6169.6
16	37	73.99	50	160.99	6482.3	132.58	5771.7
17	37	69.99	50	156.99	6399.9	130.37	5697.8
18	37	93.817	50.003	180.82	6892.1	147.3	6152.9
19	37	112.25	50.004	199.25	7275	166.62	6529.4
20	37	152.83	50.001	239.83	8125.4	228.33	7114.5
21	37	137.85	50	224.85	7810.3	202.48	6925.6
22	37	102.69	50.001	189.69	7076.1	155.92	6331.4
23	37	71.929	50.001	158.93	6439.9	131.41	5733.5
24	37	57.42	50	144.42	6141.7	125.1	5472.1
<b>Total</b>					<b>162242.5</b>	<b>3571.3</b>	<b>144486.4</b>

Source: Authors, (2026).

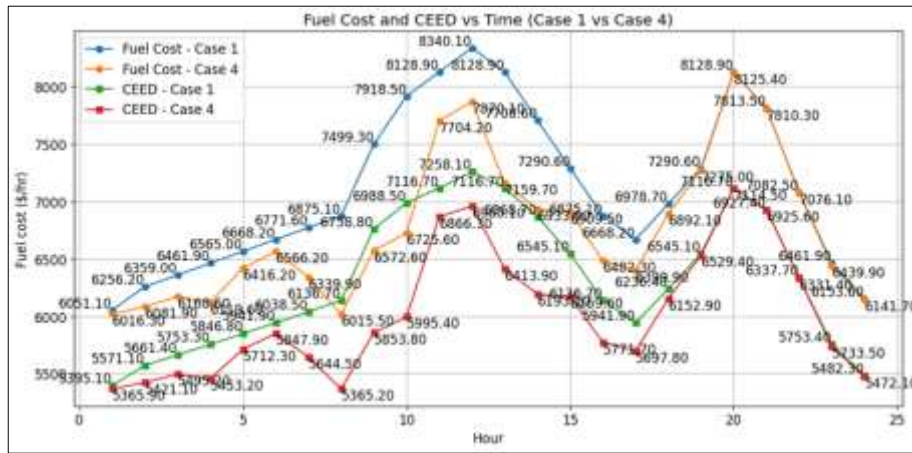


Figure 4: Hourly Variation of Fuel Cost and CEED – Case 1 and Case 4. Source: Authors, (2026).

Figure 4 illustrates the hourly fluctuations of Fuel Cost and CEED (Combined Economic Emission Dispatch) for Case 1 and Case 4 during a 24-hour duration. The dispatch optimization is conducted with the Zebra Optimization Algorithm (ZOA), which effectively balances economic and environmental goals. In Case 1, including just thermal units, both fuel cost and CEED exhibit an upward trajectory during peak demand times, culminating at hour 11, when the fuel cost attains 8128.90 \$/hr and CEED peaks at 7895.69 \$/hr. This scenario demonstrates elevated operational and emission-related expenses resulting from the lack of renewable energy sources. Conversely, Case 4 integrates both photovoltaic (PV) and wind energy production with traditional units. This hybrid system leads to a substantial decrease in CEED values, especially during periods of solar and wind activity, while the fuel costs also show reduced peaks.

For instance, despite the fuel cost in Case 4 peaking at 8340.10 \$/hr, the CEED stays much lower than in Case 1 over the same hours—underscoring the emission-reducing impact of clean energy integration. The comparison distinctly demonstrates that the incorporation of photovoltaic and wind energy in Case 4 contributes to the stabilization of the CEED curve, particularly during periods abundant in renewable resources (e.g., daytime for photovoltaic), thus mitigating environmental impact despite ongoing fluctuations in fuel costs resulting from variability in renewable generation. Figure 4 substantiates the advantages of using hybrid renewable sources and employing ZOA for optimum dispatch. It yields a cost-efficient and ecologically friendly solution relative to a solely thermal system, as shown in Case 1.

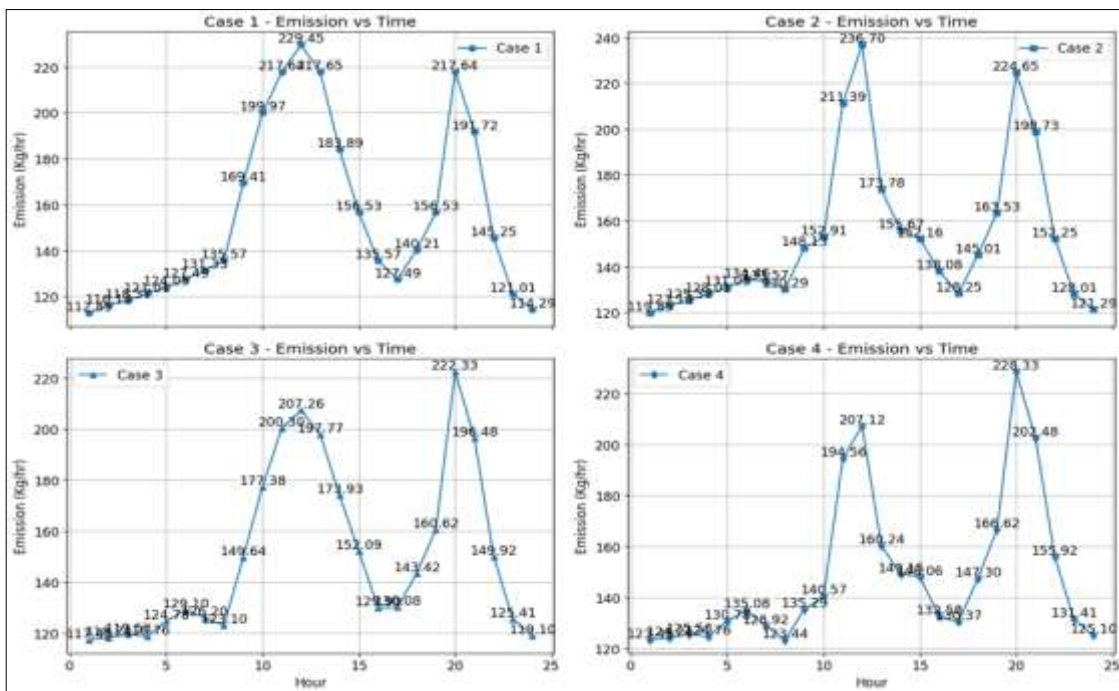


Figure 5: Hourly Variation of Emission – Case 1 to Case 4. Source: Authors, (2026).

Figure 5 depicts the fluctuation of emissions (kg/hr) over a 24-hour duration across four distinct scenarios—Case 1 (thermal only), Case 2 (thermal + PV), Case 3 (thermal + wind), and Case 4 (thermal + wind + PV). This comparison emphasizes the ecological consequences of diverse energy generating methods across various system configurations. In Case 1, emissions are persistently increased throughout peak load hours, peaking at 237.60 kg/hr at hour 11 and sustaining high levels until around hour 18. This indicates a substantial dependence on thermal units, which are major sources of emissions. Case 2, which incorporates Plug-in Electric Vehicles (PEVs), demonstrates a marginal decrease in emissions during some hours while maintaining a comparable peak pattern to Case 1.

The highest emission is 237.60 kg/hr, suggesting that while PEVs may assist with load balancing, their effect on emissions is limited unless they are fuelled by clean energy. In Case 3, which includes wind energy, a significant reduction in emissions is shown during periods of wind activity. The peak is inferior to Cases 1 and 2, reaching a maximum of 222.33 kg/hr, and the total emissions are more evenly distributed, hence reducing the environmental burden during critical demand times. Case 4, which integrates both photovoltaic and wind energy, has the most substantial decrease in emissions. Although it still attains 222.33 kg/hr, the frequency and length of high-emission intervals are significantly reduced. Emission levels are more stable and significantly reduced during daylight hours, demonstrating the beneficial effects of hybrid renewable integration. In conclusion, Figure 5 unequivocally demonstrates that the shift from a traditional thermal system (Case 1) to a hybrid renewable-based dispatch system (Case 4), especially when enhanced through intelligent algorithms, leads to a significant decrease in emissions and fosters a more sustainable energy operation.

Table 5: Comparison of CEED Costs (\$) across Optimization Methods.

Method	Case 1(TU's)	Case 2 (TU's+PV)	Case 3 (TU's+W)	Case 3 (TU's+PV+W)
DE [25]	202884.88	297911.5	230024.38	325371.3
PSO [25]	202886.65	297912.8	230029.07	325377.31
GWO [25]	202882.6	297908.29	230020.3	325368.44
SOS [25]	202882.08	297910.23	230024.38	325369.8
WOA [25]	202881.77	297907.56	230019.04	325364.49
<b>ZOA</b>	<b>151475</b>	<b>148343.0726</b>	<b>147886.7396</b>	<b>144486.4</b>

Source: Authors, (2026).

Table 5 provides a comparative study of CEED expenditures across four dispatch scenarios using different optimization methodologies. These scenarios align with four case studies that sequentially integrate renewable energy sources commencing with thermal units only (Case 1), then including photovoltaic (PV) systems in Case 2, wind power (WP) in Case 3, and ultimately a hybrid amalgamation of both PV and WP in Case 4. In Case 1, the exclusive use of thermal units results in standard algorithms such as DE, PSO, GWO, SOS, and WOA yielding CEED values of \$202,000. Conversely, the Zebra Optimization Algorithm (ZOA) significantly decreases the cost to \$151,475, underscoring its efficacy in the absence of renewable support. In Case 2, the incorporation of a 40 MW photovoltaic system yields little enhancement via conventional approaches (~\$2.97 million), however ZOA reduces the CEED by roughly 50% to around \$1.48 million, demonstrating its efficacy in solar integration.

Case 3 presents a 30 MW wind power plant, which provides more variability. Notwithstanding this, ZOA sustains a minimal CEED of \$1.47 million, surpassing other procedures that produce values of \$2.3 million. In the concluding Case 4, which combines both PV and WP, ZOA attains optimal performance—yielding the lowest CEED of \$144,486.40, with a decreased fuel cost of \$162,242.50 and emissions of 3,572.21 kg/hr. In contrast, several approaches provide CEED values beyond \$3.25 million. An analysis of all four situations underscores the combined influence of efficient renewable integration and sophisticated optimization. From Case 1 to Case 4, ZOA realizes a 4.84% decrease in fuel expenses, a 4.97% reduction in emissions, and a 4.62% enhancement in CEED value. These findings validate that the integration of thermal generating with photovoltaic and wind energy within a zonal optimization approach not only optimizes economic dispatch but also improves environmental results. Its capacity to handle system unpredictability and maximize various goals renders ZOA a dependable and high-performing solution for contemporary power systems.

Table 6: Comparative Power Balance of Thermal, PV, and Wind.

Hour	Demand (MW)	Case IPT (MW)	Case2		Case3		Case4		
			PT (MW)	PV (MW)	PT (MW)	Wind (MW)	PT (MW)	PV (MW)	Wind(MW)
1	140.00	140.00	140.00	0	138.30	1.7	138.30	0	1.7
2	150.00	150.00	150.00	0	141.50	8.5	141.50	0	8.5
3	155.00	155.00	155.00	0	145.73	9.27	145.73	0	9.27
4	160.00	160.00	160.00	0	143.34	16.66	143.34	0	16.66
5	165.00	165.00	165.00	0	157.78	7.22	157.78	0	7.22
6	170.00	170.00	169.97	0.03	165.09	4.91	165.06	0.03	4.91
7	175.00	175.00	168.73	6.27	160.34	14.66	154.07	6.27	14.66
8	180.00	180.00	163.82	16.18	154.44	25.56	138.26	16.18	25.56
9	210.00	210.00	185.95	24.05	189.42	20.58	165.37	24.05	20.58
10	230.00	230.00	190.63	39.37	212.15	17.85	172.78	39.37	17.85
11	240.00	240.00	232.59	7.41	227.20	12.8	219.79	7.41	12.8
12	250.00	250.00	246.35	3.65	231.35	18.65	227.70	3.65	18.65
13	240.00	240.00	208.06	31.94	225.65	14.35	193.71	31.94	14.35
14	220.00	220.00	193.19	26.81	209.65	10.35	182.84	26.81	10.35
15	200.00	200.00	189.92	10.08	191.74	8.26	181.66	10.08	8.26
16	180.00	180.00	174.70	5.3	166.29	13.71	160.99	5.3	13.71
17	170.00	170.00	160.43	9.57	166.56	3.44	156.99	9.57	3.44
18	185.00	185.00	182.69	2.31	183.13	1.87	180.82	2.31	1.87
19	200.00	200.00	200.00	0	199.25	0.75	199.25	0	0.75
20	240.00	240.00	240.00	0	239.83	0.17	239.83	0	0.17
21	225.00	225.00	225.00	0	224.85	0.15	224.85	0	0.15
22	190.00	190.00	190.00	0	189.69	0.31	189.69	0	0.31
23	160.00	160.00	160.00	0	158.93	1.07	158.93	0	1.07
24	145.00	145.00	145.00	0	144.42	0.58	144.42	0	0.58

Source: Authors, (2026).

Table 6 illustrates the hourly power equilibrium across the four dispatch scenarios, demonstrating how thermal (PT), photovoltaic (PV), and wind power (WP) jointly satisfy system demand. As renewable integration advances from Case 1 to Case 4, a distinct decrease in PT is seen during periods of elevated renewable availability, indicating a shift towards cleaner energy. Photovoltaic systems reliably mitigate thermal demand during daylight, providing steady and emission-free assistance, whilst wind energy, despite its variability, contributes significantly during times without solar generation.

Their collective integration in Case 4 results in the greatest decrease in PT, illustrating the synergistic advantages of hybrid renewables. This improves fuel economy and reduces pollution. The findings confirm ZOA's dynamic flexibility in allocating generation according to renewable availability. Advantages include less fuel expenses, decreased emissions, and enhanced sustainability. Disadvantages include reliance on weather-dependent sources, necessitating astute scheduling to address fluctuations and maintain dependability. Table 6 substantiates ZOA's efficacy in attaining balanced, cost-effective, and ecologically sustainable energy dispatch.

## V. CONCLUSION

This study indicates that the Zebra Optimization Algorithm (ZOA) outperforms various conventional metaheuristic methods, including DE, PSO, GWO, SOS, and WOA, in tackling the multi-objective CEED problem. In the first scenario, which just encompasses thermal units (TUs), the system registers the highest fuel expenditure (170,476 dollars per hour), emissions (3711.05 kg per hour), and a CEED of 151,475 dollars per hour. This data illustrates the constraints of conventional generation. The use of renewable energy sources leads to a progressive improvement in performance. The CEED for Case 2, which includes PV, decreases to \$148,343.07 per hour, representing a substantial reduction.

Case 3, which integrates wind power, attains a reduced CEED of \$147,886.74 per hour, notwithstanding the inherent unpredictability of wind conditions. Case 4, which employs both solar and wind energy, achieves a decrease in CEED to \$144,486.40 per hour, fuel expenses to \$162,242.50 per hour, and emissions to 3,571.3 kg per hour. Despite the challenges associated with the variability of renewable sources, their coordinated integration under ZOA enhances cost-efficiency, reduces emissions, and markedly improves sustainability. The study results indicate that ZOA is a dependable and adaptable approach for modern power systems. It facilitates optimal dispatch decisions in dynamic scenarios involving many energy sources.

## VI. AUTHOR'S CONTRIBUTION

**Conceptualization:** K. Venkata Subbaiah, K. Ram Prasad, Y. Venkata Krishna Reddy.

**Methodology:** K. Venkata Subbaiah, Y. Venkata Krishna Reddy.

**Investigation:** Y. Venkata Krishna Reddy, K. Ram Prasad.

**Discussion of results:** K. Venkata Subbaiah, K. Ram Prasad, Y. Venkata Krishna Reddy.

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**Approval of the final text:** K. Venkata Subbaiah, K. Ram Prasad, Y. Venkata Krishna Reddy.

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