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Combined Heat and Power Economic Dispatching within Energy Network using Hybrid Metaheuristic Technique

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Abstract: Combined heat and power (CHP) plants have opportunities to work as distributed power generation for providing heat and power demand. Furthermore, CHP plants contribute effectively to overcoming the intermittence of renewable energy sources as well as load dynamics. CHP plants need optimal solution(s) for providing electrical and heat energy demand simultaneously within the smart network environment. CHP or cogeneration plant operations need appropriate techno-economic dispatching of combined heat and power with minimising produced energy cost. The interrelationship between heat and power development in a CHP unit, the valve point loading effect, and forbidden working regions of a thermal power plant make the CHP economic dispatch's (CHPED) objective function discontinuous. It adds complexity in the CHPED optimisation process. The key objective of the CHPED is operating cost minimisation while meeting the desired power and heat demand. To optimise the dispatch operation, three different algorithms, like Jaya algorithm, Rao 3 algorithm, and hybrid CHPED algorithm (based on first two) are adopted containing different equality and inequality restrictions of generating units. The hybrid CHPED algorithm is developed by the authors, and it can handle all of the constraints. The success of the suggested algorithms is assessed on two test systems; 5-units and 24-unit power plants.

Keywords: combined heat and power economic dispatch (CHP-ED); CHPED optimisation; heat and power dispatching; CHP plants; hybrid CHPED algorithm

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1. Introduction

In the process of converting fossil fuels into electrical power, conventional thermal power stations produce a large amount of thermal energy without adequate storage and use. This leads to huge losses of thermal energy. Therefore, the effectiveness of traditional power plants is reduced by 50% to 60% [1–3]. Rising levels of carbon dioxide in the air and global warming have prompted the industry to integrate power and heat more efficiently within the energy networks. Hence, the effective planning of energy resources to meet the different loads has become more important. Therefore, it is required to have appropriate operational strategies for supplying the combined heat and power, considering the operational constraints of the CHP plants [4]. Operation of CHP plants is very economical and can contribute effectively in overcoming the intermittence of renewable energy sources, as well as in primary/secondary control of the power system. CHP plants can increase the total efficiency by 90%, decrease the operational cost by about 10% to 40% with appropriate operational strategies, and reduce CO_2 releases by 13% to 18% [5,6]. The CHP plants need appropriate strategies for providing combined heat and power economic dispatching (CHEPD) for fulfilling the CHP demand, considering the technical and operational constraints. The motive behind CHPED is to find the profitable method for utilizing the existing generating plants to satisfy the electric power requirements and CHP requirements from CHP plants to fulfil the load demand and operating them within the constraints.

When optimising the CHPED, various operating techniques, such as constraints on the equality and inequality of power and heat units, must be considered [7]. The CHEPD optimisation problem is no longer linear and convex because of the valve point loading (VPL) effect and prohibited operating zones (POZs) of a typical thermal power system. There are some technical difficulties with CHPED optimisation because of the joint reliance of heat-power in the CHP plant.

In the literature [8–18], several optimising techniques have been recommended to fix the CHPED issues. These approaches can be divided as: (1) Mathematical and (2) Meta-heuristic. Mathematical techniques contain quadratic models [8], the Lagrange method [9], the bi-layer Lagrange approach [10], branch-bound algorithm [11], and so on. Such approaches are limited for handling the non-convexity of optimisation functions. As a result, resolving the CHPED issue is a significant challenge. These shortcomings can be addressed by developing some new methods for CHPED using metaheuristics. The metaheuristic techniques can be classified into single-objective and multi-objective frameworks to solve the CHPED optimisation process.

In single objective problem formulation, minimisation of the operating cost of the CHPED issue is the top priority. Thus, to resolve the CHPED issue, a penalty factor-based genetic algorithm (GA) is applied in [12]. While in [13], evolutionary programming (EP) is applied to formulate the CHPED issue. In [14], a real-coded GA, based on self-adaptation is used to address the CHPED issue, based on mutation/crossover phenomena, and the constraints are handled by a penalty parameter. However, in [15], researchers considered a harmony searching process to minimise the fuel price by the pitch factor adjustment of the search operators. A firefly algorithm is explained to formulate the CHPED issue in [16]. An invasive weed technique is used to formulate the CHPED issue which is influenced by the environmental weed allocation and colonial procedures [17]. While in [18], the author proposed a hybrid biogeography-based method with simulated annealing (SABBO) to examine the constrained CHPED problem.

But in the research studies [12–18], the VPL effect of a thermal power unit and transmission loss have not been looked at. To overcome these issues, an exchange market algorithm (EMA) is proposed to formulate the CHPED issue, considering the VPL effect and transmission loss [19]. A cuckoo search algorithm (CSA) is also found suitable to resolve the constrained optimisation, due to fewer design variables and computational timings [20]. The gravity search algorithm (GSA) was employed by Beigvand et al. [21] to describe the CHPED difficulties. However, in [22], to handle constraints, an improved differential evolution technique as well as a revised repair process were used. A modified group search optimisation (MGSO) is suggested in [23] to solve the CHPED. In [24], a self-regulating PSO is used to find the optimum scheduling of CHPED.

The POZs of thermal power units make the CHPED problem more difficult to address due to the fuel supply. Only a few optimisation procedures are realised including POZs. For handling the non-convexity of the CHPED issue, a group search optimisation, based on opposition is applied, which is based on the opposition guess of the search particles [25]. While in [26], the best outcome of CHPED is attained by the enhanced particle swarm optimisation (PSO), wherever the Gaussian distribution factor is used to increase the global searching phenomena. In [27], the group search optimisation for lowering the operational price and improve the accuracy of the CHPED issue is explained. However, in [28], a hybrid bat-arbitrary bee colony method is established to obtain the benefits over the basic bat and bee colony methods. A heat transfer search technique has been proposed, considering the conduction, convection, and radiation to effectively solve the CHPED problem [29]. Moreover, Zou et al. [30] have described the improved GA, with distinct crossover and mutation steps. However, in [31], a self-regulating PSO gives a better convergence speed when VPL and POZs are taken. To report the CHPED issue with various limitations, a bio-geography-based PSO is established, which uses migration operators to reach the best location [32].

However, in [33], generation fuel cost is minimised by a hybrid metaheuristic algorithm considering different operational constraints. Where as in [34], a high level CHPED framework, including 24-units and 84-units has been formulated using a multi-player harmony search method. An optimal model of CHPED is introduced in [35], where electric boilers are used to reduce cost and wind curtailment. While in [36], a hybrid heap-based jellyfish searching method is applied to explain a non-convex CHPED issue. Where the exploration/exploitation is used to allocate optimum results of thermal and electrical energy generation.

Several research studies have been carried out for a multi-objective framework, where the objective function is taken as the minimisation of cost, as well as emissions. As in [37], the problem is solved via deterministic and stochastic methods, including various complications. While in [38], the multi-objective multi versus optimisation (MOMVO) algorithm is proposed to resolve the environmental CHPED issue. A hybrid enhanced GA and PSO is proposed to obtain the best outcomes of a combined economic/environmental dispatch (CEED) issue [39]. However, in [40], a kho-kho optimisation (KKO) technique is applied to resolve the CHPED and CEED issues.

However, apart from the above research studies, some of the studies have been carried out, where metaheuristic and mathematical methods were used together. As in [41], a time varying accelerative coefficient-based PSO (TVAC-PSO) was created to examine the CHPED issue. In [42], Basu proposed a non-dominated sorting GA-II for analysing the CHPED issue. This is employed in conjunction with a real-coded genetic algorithm because binary values create complexities in search spaces with high precision. While in [43], a real coded GA (RC-GA) through progressive transformation evolution is proposed for the CHP unit, considering VPL and network losses. In [44], Jena et al. suggested a Gaussian genetic change in the basic DE for enhancing the search functionality. While in [45], TVAC-PSO is adopted to explain the economic emission dispatch issue considering losses. The Monte-Carlo technique is used to implement a stochastic model to handle the real-world scenario. In [46], Beigvand et al. have suggested a hybrid gravitational search TVAC-PSO method to explain the large-scale CHPED issue. In [47], a Lagrangian-relaxation-based alternative method is implemented where the non-convexity of the CHP component is separated in numerous convex areas utilizing the Big-M technique for solving the CHPED issue successfully. In [48], the exchanged market algorithm EMA is joined with the non-dominated TVAC-PSO, to resolve the dispatch problem

The state-of-the-art literature review has found that the mathematical modelling of CHP units with a thermal power unit is quite complex. Because of the VPL effect and the restricted working region of thermal power units, the entire solution for CHPED becomes non-convex, non-linear, and non-differentiable. Furthermore, the viability of the CHP unit is reliant on both power generation and heat production. To solve this complex system, several mathematical and metaheuristic-based methodologies have been proposed. However, most of them have struggled to find an optimal solution due to various generating unit constraints. Many algorithms have their own algorithm-specific parameters. The tuning of such variables makes the CHPED issue more challenging.

For solving the above difficulties, in the current research study, three simple meta-heuristic algorithms, such as (i) Rao 3 algorithm [49], (ii) Jaya algorithm [50], and (iii) hybrid CHPED algorithm (i.e., developed by the authors, based on (i) and (ii)) are applied for solving the complex CHPED issues. The author's contribution in the present study is explained by the following points.

- The hybrid CHPED optimisation algorithm is a newly developed algorithm by the authors to solve the constrained optimisation problem;
- The hybrid CHPED algorithm is developed by the combination of the basic Jaya algorithm and Rao 3 algorithm;
- The hybrid CHPED algorithm is used to solve the constrained and unconstrained optimisation problems of CHP operations;
- To handle all of the constraints, the exterior penalty factor method is used to obtain the desired solutions.

All three methods are used by selecting the best and worst candidates and they have only two designing variables: size of the population and iterations. There is no need for any other algorithm specific variables. The Rao 3 method is based on random interactions between the candidate throughout the iteration, but it is not required in the developed hybrid CHPED algorithm. To analyse the CHPED problem accurately, the VPL effect and POZs of the power plants are taken. For a better understanding, the viable working areas of the CHP unit are taken into account for minimising the total operating price. In this study, two test case systems, a 5-unit and a 24-unit, are used to evaluate the proposed technique (details are presented in Section 4). The results of the developed hybrid CHPED algorithm is compared with the basic Jaya algorithm and Rao 3 algorithm. It is found that the hybrid CHPED optimisation algorithm performs better. The results of these three methods are also compared to that of a well-known research method to indicate their superiority.

The article is organised as follows: Section 2 provides the computational models of the CHP economic load dispatch optimisation. Section 3 contains the proposed technique. Section 4 provides an evaluation of the two cases studied and last, Section 5 provides the paper's conclusion and the future scope.

2. Mathematical Modelling of CHPED

2.1. Objective Function

The aim of CHPED is to recognise a profitable way for scheduling heat-power generation to meet load demands while maintaining all restrictions. The mathematical equation for the total operational price function is explained by Equation (1) [4,51,52].

$$\text{Min C } = \sum_{i=1}^{N_{TH}} C_i(P_i^{TH}) + \sum_{j=1}^{N_{CHP}} C_j\left(P_j^{CHP},\ H_j^{CHP}\right) + \sum_{k=1}^{N_H} C_k(H_k^H)\ (\$/h) \tag{1}$$

where, C is the total operational price; $C_i\left(P_i^{TH}\right)$, $C_j\left(P_j^{CHP},\ H_j^{CHP}\right)$, and $C_k\left(H_k^H\right)$ are the fuel price function of thermal power; CHP and heat units are denoted by i^{TH} j^{TH}, and k^{TH} unit, respectively. The number of thermal power, CHP, and heat units are $N_{TH,}$ $N_{CHP,}$ and $N_{H.}$ P_i^{TH} and P_j^{CHP} are the power generation of the thermal power and heat unit. H_j^{CHP} and H_k^H are the heat production of CHP and the heat unit.

The thermal power plant's price function is explained by Equation (2) [53].

$$\sum_{i=1}^{N_{TH}} C_i(P_i^{TH}) = \sum_{i=1}^{N_{TH}} [a_i P_i^{TH^2} + b_i\ P_i^{TH} + c_i\ ]\ (\$/h) \tag{2}$$

where, a_i, $b_{i,}$ and c_i are the price coefficients of the thermal power unit.

As a result of the VPL effect, the optimisation function shows non-convexity and nonlinearity. This creates local minimal points. A rectified sine term is added in the objective function for exact analysis. The objective function considering VPL is represented in Equation (3) [54,55].

$$\sum_{i=1}^{N_{TH}} C_i(P_i^{TH}) = \sum_{i=1}^{N_{TH}} [a_i P_i^{TH^2} + b_i\ P_i^{TH} + c_i\ + |e_i\ \sin\{f_i\ (P_i^{TH^{min}} - P_i^{TH})\}\ |]\ (\$/h) \tag{3}$$

where e_i and f_i are the price coefficient due to VPL.

The price function for CHP and the heat-only unit is explained by Equations (4) and (5) [56–58].

$$\sum_{j=1}^{N_{CHP}} C_j\left(P_j^{CHP},\ H_j^{CHP}\right) = \sum_{j=1}^{N_{CHP}} [a_j\ P_j^{CHP^2} + b_j\ P_j^{CHP} + c_j + d_j H_j^{CHP^2} +\ e_j H_j^{CHP} +\ f_j\ P_j^{CHP}\ H_j^{CHP}]\ (\$/h) \tag{4}$$

$$\sum_{k=1}^{N_H} C_k(H_k^H) = \sum_{k=1}^{N_H} a_k H_k^{H^2} + b_k H_k^H + c_k \ (\$/h) \tag{5}$$

where,$C_j\left(P_j^{CHP}, H_j^{CHP}\right)$ is the price function and a_j, b_j, c_j, d_j, e_j, and f_j are the price coefficient of the CHP unit. $C_k\left(H_k^H\right)$ is the price function and a_k, b_k, and c_k are the price coefficient of the heat unit.

2.2. Constraints

2.2.1. Power Balancing

The overall electricity produced by the thermal and CHP units would match the whole amount of power required shown in Equation (6) [56–58].

$$\sum_{i=1}^{N_{TH}} P_i^{TH} + \sum_{j=1}^{N_{CHP}} P_j^{CHP} = P_d \tag{6}$$

where P_d are the power requirements.

2.2.2. Heat Balancing

The complete heat production by the CHP and heat unit would correspond to all of the heat requirements, as explained by Equation (7) [56–58].

$$\sum_{j=1}^{N_{CHP}} H_j^{CHP} + \sum_{k=1}^{N_H} H_k^H = H_d \tag{7}$$

where H_j^{CHP} and H_k^H are the heat production of j^{TH} CHP and the k^{TH} heat unit.

2.2.3. Limitation of the Power Unit

The capacity limit of the power unit is explained by Equation (8) [56–58].

$$P_i^{TH^{min}} \leq P_i^{TH} \leq P_i^{TH^{max}}; \text{where } i = 1, \ldots\ldots N_{TH} \tag{8}$$

where $P_i^{TH^{min}}$ and $P_i^{TH^{max}}$ express the lowest and highest bounds of i^{TH} power unit in MW.

2.2.4. Limitation of the CHP Unit

The capacity limit of the cogeneration unit is given by Equations (9) and (10) [56–58].

$$P_j^{CHP,min}\left(H_j^{CHP}\right) \leq P_j^{CHP} \leq P_j^{CHP,max}\left(H_j^{CHP}\right); \text{ where } j = 1, \ldots\ldots N_{CHP} \tag{9}$$

$$H_j^{CHP,\,min}\left(P_j^{CHP}\right) \leq H_j^{CHP} \leq H_j^{CHP,\,max}\left(P_j^{CHP}\right); \text{ where } j = 1, \ldots\ldots N_{CHP} \tag{10}$$

where $P_j^{CHP,\,min}\left(H_j^{CHP}\right)$ and $P_j^{CHP,\,max}\left(H_j^{CHP}\right)$ are the lowest and highest bounds of power delivered by j^{TH} CHP unit in MW and the function of heat production expressed via H_j^{CHP}, $H_j^{CHP,\,min}\left(P_j^{CHP}\right)$ and $H_j^{CHP,\,max}\left(P_j^{CHP}\right)$ are lowest and highest heat production of j^{TH} CHP unit in MWth and the function of power delivered expressed by P_j^{CHP}.

2.2.5. Limitation of the Heat Unit

The capacity limit of the heat unit is given by Equation (11) [56–58].

$$H_k^{H,min} \leq H_k^H \leq H_k^{H,max}\ ; \text{ where } k = 1, \ldots\ldots., N_H \tag{11}$$

where $H_k^{H,min}$ and $H_k^{H,max}$ are the lowest and highest bound of the heat unit.

2.2.6. Working of the POZs in the Power Unit

Because of the physical characteristics of power plants, generators are restricted to operate in some zones. These are known as the POZs of power plants and the consideration of POZs make the cost curve discontinuous, as expressed by Equation (12) [56–58].

$$\begin{cases} P_i^{TH^{min}} \le P_i^{TH} \le P_{i,1}^{TH^L} \\ P_{i,m-1}^{TH^U} \le P_i^{TH} \le P_{i,m}^{TH^L}, \quad \text{where} \quad m = 2, 3, \ldots\ldots Z_i \\ P_{i,zi}^{TH^u} \le P_i^{TH} \le P_i^{TH^{max}} \end{cases} \tag{12}$$

where, $P_{i,m}^{TH^L}$ and $P_{i,m}^{TH^U}$ are the lowest and highest bounds of the POZ. Z_i is the number of POZs for i^{TH} power unit.

2.2.7. Feasible Operating Region (FORs) of the CHP Unit

CHP plants provide electricity and heat from a single fuel source. The production of heat and electricity in CHP units is duel dependent. The mathematical formulation of the CHP unit is therefore very complex [59].

Combining the limits of Equations (9) and (10), the two-dimensional permissible working range of the CHP units can obtained and given by $\{(H_j^{CHP}, P_j^{CHP}) : P_j^{CHP,min}(H_j^{CHP}) \le P_j^{CHP} \le P_j^{CHP,max}(H_j^{CHP}), H_j^{CHP,\ min}(P_j^{CHP}) \le H_j^{CHP} \le H_j^{CHP,\ max}(P_j^{CHP})\}$.

The FOR of any cogenerating unit is bounded by the heat and power plane in an enclosed region ABCDA, as depicted in Figure 1.

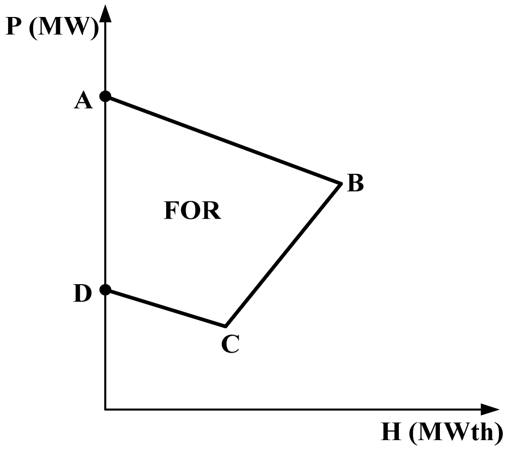

Figure 1. FOR of a CHP unit.

2.3. Constraint Handling Technique

In the present article, the exterior penalty factor method is applied for handling all constraints, that panelise impractical solutions during the iteration. It converts the constrained optimisation problem into an unconstrained one. A suitable value of penalty is applied after various trials considering all limitations [44].

It is preferable to normalise each constraint, since they all have a distinct order of magnitude. Let us say that non-linear problem X = (X_1, X_2, ... , X_N) with N decisioning parameters. The normalised optimisation function can be written in the following manner:

$$\text{Min C } (X_1, X_2, \ldots\ldots, X_N)$$

$$G_i(X_1, X_2, \ldots\ldots, X_N) = 0;\ \text{where } i = 1, 2, \ldots\ldots \text{Ne}$$

$$H_j(X_1, X_2, \ldots\ldots, X_N) \le 0;\ \text{where } j = 1, 2, \ldots\ldots \text{Nie}$$

where Ne and Nie are the equality and inequality constraints.

Assume any value X_1, which is the infeasible point, then $G_i(X_1) \neq 0$, for the equality constraint and $H_j(X_1) > 0$, for the inequality constraint. To overcome this problem, a suitable value of penalty is imposed in terms of R. The value of R is projected after various trials for obtaining the optimised values. The updated objective function is given in Equation (13).

$$F(X) = \text{Min } C(X_1, X_2, \ldots, X_N) + R\left(\sum_{i=1}^{Ne} G_i^2(X) + \sum_{j=1}^{Nie} \text{Max}(0, H_j(X)^2)\right) \tag{13}$$

3. Implementation of the Optimisation Algorithms in the CHPED Formulation

For solving the CHPED issue effectively, three distinct optimisation algorithms are employed: (1) the Rao 3 algorithm [49], (2) Jaya algorithm [50], and (3) hybrid CHPED algorithm. The hybrid CHPED algorithm is developed by the authors, which is a combination of the basic Jaya algorithm and Rao 3 algorithm. All three algorithms are based on the best and worst candidate selection. In the Rao 3 algorithm, there is a random communication among the candidates, but it is not required in the hybrid CHPED algorithm, which makes it simpler than the Rao 3 algorithm. Furthermore, the hybrid combination performs better, as compared to the individual algorithm, in relation to accuracy and reliability. The mathematical equations for Jaya, Rao 3, and hybrid CHPED algorithm are expressed by Equation (14) to Equation (16), respectively. In this study, the programming technique is outlined in the following steps. The flow charts of three algorithms are demonstrated in Figure 2.

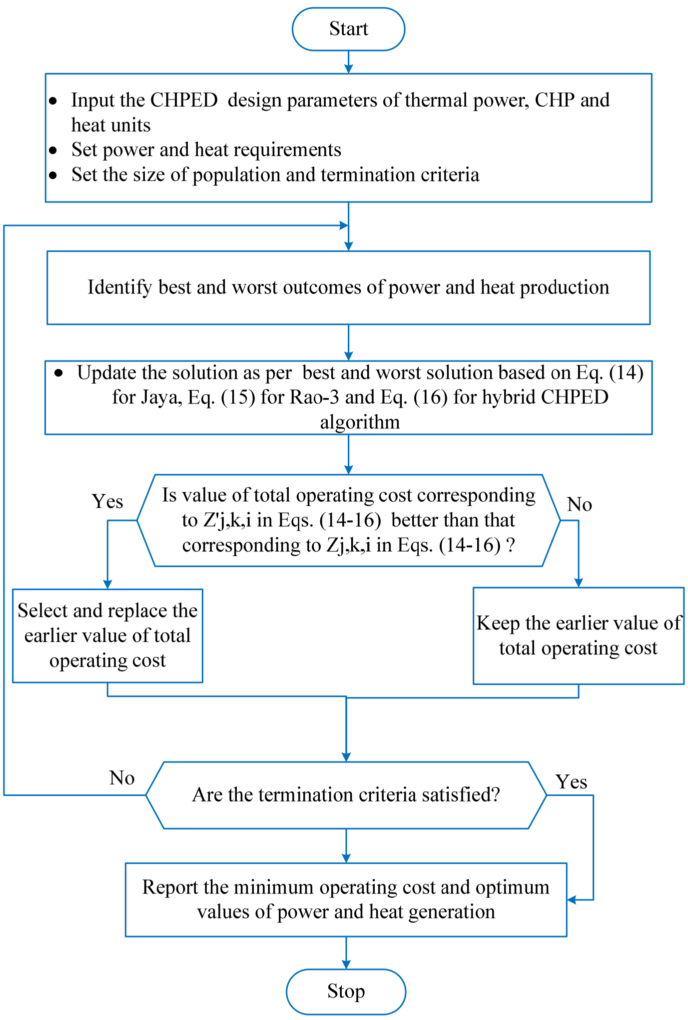

Figure 2. Flow chart of the proposed CHPED algorithm.

Step 1. Design the fitness function: Formulate the mathematical equation for the total operational price of the CHPED problem as fitness function F (Z) to be minimised;

Step 2. Allocate the input variables: Insert the input variables for power, CHP, and heat units. Assign the required thermal and electrical power demands. Furthermore, fix the population size (m) and termination criteria (n);

Step 3. Select the feasible solutions: Obtain the minimum and maximum value of F(Z), as $F(Z)_{BEST}$ and $F(Z)_{WORST}$ during the iteration. Select the respective power and heat output $Z_{j,k,i}$ of F(X). Where, $Z_{j,k,i}$ is the value of j^{TH} designing parameter for k^{TH} particle throughout i^{TH} iteration;

Step 4. Update the solutions: Update the results on the basis of lower and higher values of F(Z) for the Jaya algorithm, Rao 3 algorithm, and hybrid CHPED algorithm, based on Equations (14)–(16). Modify the power and heat output results given by the following equation:

$$Z'_{j,k,i} = Z_{j,k,i} + r_{1,j,i}\left(Z_{j,BEST,i} - \left|Z_{j,k,i}\right|\right) - r_{2,j,i}\left(Z_{j,WORST,i} - \left|Z_{j,k,i}\right|\right) \tag{14}$$

$$Z'_{j,k,i} = Z_{j,k,i} + r_{1,j,i}\left(Z_{j,BEST,i} - \left|Z_{j,WORST,i}\right|\right) + r_{2,j,i}\left(\left|Z_{j,k,i} \text{ or } Z_{j,l,i}\right| - \left(Z_{j,l,i} \text{ or } Z_{j,k,i}\right)\right) \tag{15}$$

$$Z'_{j,k,i} = Z_{j,k,i} + r_{1,j,i}\left(Z_{j,BEST,i} - \left|Z_{j,WORST,i}\right|\right) + r_{2,j,i}\left\{\left(Z_{j,BEST,i} - \left|Z_{j,k,i}\right|\right) - \left(Z_{j,WORST,i} - \left|Z_{j,k,i}\right|\right)\right\} \tag{16}$$

where, $Z_{j,BEST,i}$ and $Z_{j,WORST,i}$ are the best and worst outcomes of parameter j for i^{TH} iteration. $Z'_{j,k,i}$ is the improved result of $Z_{j.k.i}$. $r_{1,j,i}$ and $r_{2,j,i}$ are random values between 0 and 1.

In Equations (14) and (16), the terms "$\left(Z_{j,BEST,i} - \left|Z_{j.k.i}\right|\right)$" and "$-\left(Z_{j,WORST,i} - \left|Z_{j.k.i}\right|\right)$" are close to the best and worst outcomes, respectively.

In Equation (15), $Z_{j,k,i}$ or $Z_{j,l,i}$ represent a random interaction between the candidate 'k' and 'l', based on the fitness values and exchange the information. Set $Z_{j,k,i}$, if the fitness value of candidate k is better than candidate l, otherwise it will be $Z_{j,l,i}$. Similarly for the term $Z_{j,l,i}$ or $Z_{j,k,i}$, it is applicable, if candidate k is better than candidate l, then replace the term with $Z_{j,l,i}$, otherwise it will be $Z_{j,k,i}$.

Step 5. Locate the final outcome: If $Z'_{j,k,i}$ is better than $Z_{j.k.i,}$, then choose the updated value instead of the earlier value, or else keep the earlier value. Furthermore, report the optimum values of power and heat production for the CHPED problem. Continue this process until the termination requirements are met.

4. Results and Discussion

4.1. Test System 1

This arrangement comprises five units: one power unit, three CHP units, and one heat unit. The parameters for the considered 5-unit system are given in Appendix A (Table A1) and the considered aggregated power and heat demands are 160 MW and 220 MW. In this case, only the VPL effect is considered and the transmission losses are neglected. The size of the population and maximum iterations are set to 50 and 300. To find the accurate solution, 30 independent trials are carried out. The suitable penalty values are selected as 50, 60, and 55 for the Jaya, Rao 3 and hybrid CHPED algorithms, respectively. Table 1 displays the optimised outcome of power and heat production by the suggested Jaya, Rao-3, and hybrid CHPED algorithms. Pd* and Hd* are the total amount of power and heat demand. Table 2 give the statistical study, in relation to minimum, mean, and maximum cost, including those of GSO [23], IGA-NCM [30], and BLPSO [32]. It is found that after applying the Jaya, Rao-3 and hybrid CHPED algorithm, the minimum costs obtained are 11,753.1479 ($/h), 11,749.8400 ($/h) and 11,746.7751 ($/h), respectively (refer to Table 2). It is found that the minimum cost obtained from these three algorithms is better than that obtained from another metaheuristic optimisation algorithm. Furthermore, the developed hybrid CHPED algorithm performs better than the Jaya as well as the Rao-3 algorithms.

The minimum price convergence curve found using the suggested Jaya, Rao-3, and hybrid CHPED algorithm is depicted in Figure 3.

Table 1. Optimised values of the power-heat production of test system 1.

	JAYA Algorithm	Rao-3 Algorithm	Hybrid CHPED Algorithm
P1	41.8990	41.9101	39.2114
P2	64.0012	63.8002	60.1594
P3	10.0000	10.0000	10.0000
P4	44.1006	44.2904	50.6289
H2	95.5961	95.6299	92.8700
H3	40.0000	40.0000	40.0001
H4	24.4042	24.3700	27.1304
H5	60.0000	60.0000	60.0000
Pd*	160.0008	160.0007	159.9997
Hd*	220.0003	219.9999	220.0005

Table 2. Statistical analysis of test system 1.

Algorithm	GSO [23]	IGA-NCM [30]	BLPSO [32]	JAYA Algorithm	Rao-3 Algorithm	Hybrid CHPED Algorithm
Maximum cost ($/h)				11,780.9877	11,750.0429	11,754.3111
Mean cost ($/h)				11,764.2623	11,749.8716	11,750.6016
Minimum cost ($/h)	11,775.9485	11,759.1827	11,758.3627	11,753.1479	11,749.8400	11,746.7751
Ca ($/h)				11,753.0342	11,749.7860	11,746.2099

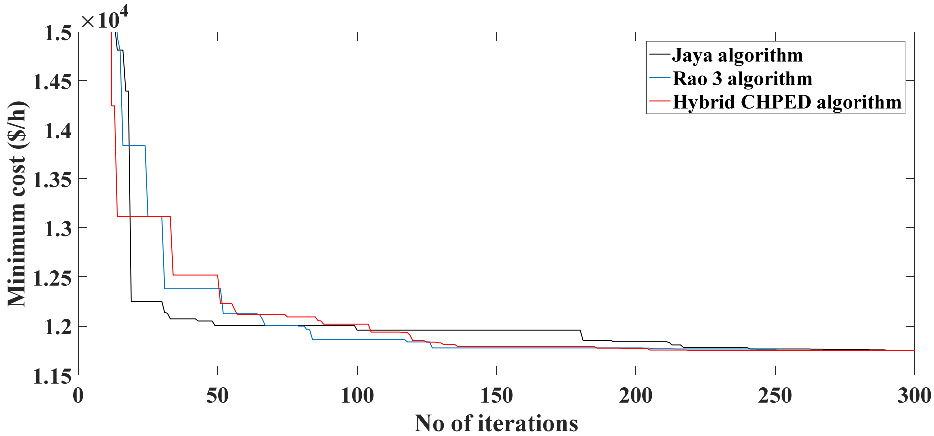

Figure 3. Minimum price convergence curve for the 5-unit test system.

4.2. Test System 2

This system includes twenty-four units: 13 power units, six CHP units, and five heat units. The cost function parameters and POZs of power plants for the 24-unit system are given in Appendix A (Tables A2 and A3). The power and heat demand is 2350 MW and 1250 MW. Test system 2 is divided into two operational modes. Case 1 is considered the only VPL effect and in case 2, the POZs are also taken with the VPL effect. The effect of transmission loss is considered as zero. To find the accurate solution, 30 independent trials are carried out. The suitable penalty values are selected as 47, 45, and 50 for the Jaya, Rao 3, and hybrid CHPED algorithms, respectively.

Case 1: Only the VPL effect is used in this case. Assume the size of the population and the maximum iterations are 50 and 1000. Table 3 displays the optimised values of the power and heat production by the suggested Jaya, Rao-3, and hybrid CHPED algorithms. Pd* and Hd* are the total amount of power and heat demand observed by the suggested method. Table 4 gives the statistical study in relation to the minimum, mean, and maximum cost, comparing with CPSO [41], TVAC-PSO [41], TLBO [60], GSA [21], and GSO [23].

Table 3. Optimised values of the power-heat production for case 1 of test system 2.

	JAYA Algorithm	Rao-3 Algorithm	Hybrid CHPED Algorithm
P1	538.5489	628.3130	628.3172
P2	299.1996	359.9973	299.1989
P3	299.2410	0.0045	299.2645
P4	109.8241	159.7227	60.0000
P5	110.0143	109.8682	109.9785
P6	110.0075	60.0000	110.4286
P7	110.2104	159.7445	109.921
P8	109.6489	159.7982	109.3241
P9	110.0014	159.6977	109.1541
P10	77.3401	115.7025	40.0000
P11	77.3999	40.0243	76.8932
P12	55.2198	55.0398	55.0023
P13	55.0842	55.0067	55.1021
P14	81.7599	81.0460	81.0004
P15	41.7546	40.0038	40.0000
P16	81.9999	81.0009	81.0215
P17	40.9091	40.0119	40.3997
P18	10.0000	10.0000	10.0017
P19	31.8381	35.0186	35.0000
H14	105.9295	105.6650	104.9916
H15	76.5214	81.0654	75.7112
H16	104.9986	105.4930	104.2509
H17	75.0011	77.3073	75.0045
H18	40.0000	40.5253	40.0008
H19	18.7016	20.7161	20.0015
H20	468.8598	459.2565	470.0489
H21	60.0000	59.9983	59.9978
H22	60.0000	59.9780	59.9993
H23	119.9956	120.0000	120.0000
H24	120.0000	119.9832	120.0000
Pd*	2350.002	2350.0006	2350.0078
Hd*	1250.008	1249.988	1250.0068

Table 4. Statistical analysis of case 1 of test system 2.

Algorithm	CPSO [41]	TVAC-PSO [41]	TLBO [60]	GSA [21]	GSO [23]	Jaya Algorithm	Rao-3 Algorithm	Hybrid CHPED Algorithm
Maximum cost ($/h)	60,076.6903	58,359.5520	58,038.5273	-	58,453.9227	57,875.5085	57,864.0758	57,863.2447
Mean cost ($/h)	59,853.478	58,198.3106	58,014.3685	-	58,217.0254	57,872.9562	57,862.6973	57,853.4180
Minimum cost ($/h)	59,736.2635	58,122.7460	58,006.9992	58,121.8640	58,122.7068	57,865.9120	57,861.1978	57,845.1922
Ca ($/h)	-	-	-	-	-	57,865.8282	57,861.0336	57,845.0550

In Table 4, after applying the Jaya, Rao-3 and hybrid CHPED algorithm, the minimum price obtained is 57,865.9120 ($/h), 57,861.1978 ($/h), and 57,845.1922 ($/h), respectively. It is found that the minimum cost obtained from these three algorithms is better than that obtained from another metaheuristic optimisation algorithm. Furthermore, the newly applied hybrid CHPED algorithm performs better than the Jaya, as well as the Rao-3 algorithms. The minimum price convergence curve found using the proposed Jaya, Rao-3, and hybrid CHPED algorithm is shown in Figure 4.

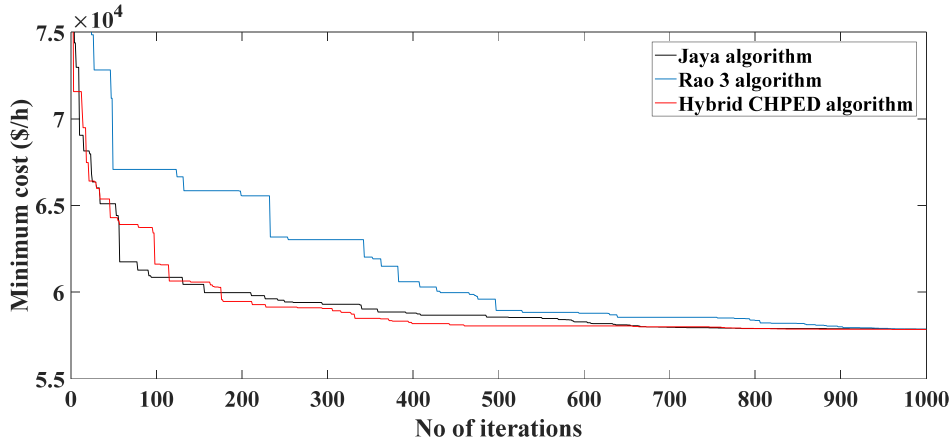

Figure 4. Minimum price convergence curve for case 1 of test system 2.

Case 2: The VPL effects and POZs are considered together in this case. Assume the size of the population and the maximum iterations are 50 and 1000. Table 5 displays the optimum results of the power and heat production by the suggested Jaya, Rao-3, and hybrid CHPED algorithms. Pd* and Hd* are the power and heat demand observed by the suggested method. Table 6 gives the statistical study in relation to the minimum, mean, and maximum cost, compared with GSO [27], OGSO [25], CSO-PPS [61], and HTS [29]. It can be seen from Table 6, after applying the Jaya, Rao-3, and hybrid CHPED algorithms, the minimum price observed is 57,953.0855 ($/h), 57,895.6050 ($/h), and 57,803.6789 ($/h), respectively. Ca is the amended minimum cost, which is calculated. It is observed by Table 6 that the minimum cost attained from the Jaya algorithm is slightly higher than OGSO [25] and CSO-PPS [61] but better than GSO [27] and HTS [29]. It is also found that the Jaya, Rao-3 and hybrid CHPED algorithm performs better than other well-established algorithms. The minimum price convergence curve found using the suggested Jaya, Rao-3, and hybrid CHPED algorithm is shown in Figure 5.

Table 5. Optimised values of the power-heat production for case 2 of test system 2.

	JAYA Algorithm	Rao-3 Algorithm	Hybrid CHPED Algorithm
P1	628.5248	628.9019	629.3246
P2	299.2548	359.7078	299.1948
P3	224.5712	0.0210	299.8547
P4	60.0000	109.8662	60.0000
P5	159.8512	159.7324	109.7652
P6	60.0000	60.0000	109.7209
P7	159.5801	109.8561	109.7103
P8	60.0004	109.9098	109.5248
P9	159.2304	159.7088	109.8411
P10	40.0000	114.5164	40.0000
P11	40.0000	77.3854	75.6012
P12	55.0125	55.0000	55.0000
P13	92.0548	118.2993	55.0798
P14	89.3021	81.0225	81.0001
P15	44.7158	40.0000	40.0046
P16	86.5514	81.0000	81.0000
P17	45.0007	40.0293	40.3777
P18	10.0228	10.0000	10.0000
P19	36.3312	35.0000	35.0000
H14	109.6998	109.9887	104.3201
H15	79.0241	79.2938	79.0007
H16	107.8642	105.8367	104.2014

Table 5. *Cont.*

	JAYA Algorithm	Rao-3 Algorithm	Hybrid CHPED Algorithm
H17	80.0000	78.4357	75.0000
H18	40.0000	40.8931	39.0012
H19	20.0018	21.0661	20.0000
H20	453.4211	454.0547	468.5218
H21	60.0000	59.9989	60.0000
H22	59.9943	59.9983	60.0000
H23	120.0000	120.0000	120.0000
H24	119.9997	120.0000	120.0000
Pd*	2350.0052	2349.9575	2349.9998
Hd*	1250.005	1249.566	1250.0452

Table 6. Statistical analysis of case 2 of test system 2.

Algorithm	GSO [27]	OGSO [25]	CSO-PPS [61]	HTS [29]	Jaya Algorithm	Rao-3 Algorithm	Hybrid CHPED Algorithm
Maximum cost ($/h)	58,119.1635	57,953.3522	57,945	57,960.73	58,368.95	57,897.8129	57,803.7126
Mean cost ($/h)	58,114.6060	57,946.0934	57,940	57,959.92	58,227.43	57,896.7356	57,803.6984
Minimum cost ($/h)	58,110.090	57,942.5577	57,935	57,959.41	57,953.0855	57,895.6050	57,803.6789
Ca ($/h)	-	-	-	-	57,952.5961	57,895.5463	57,803.5143

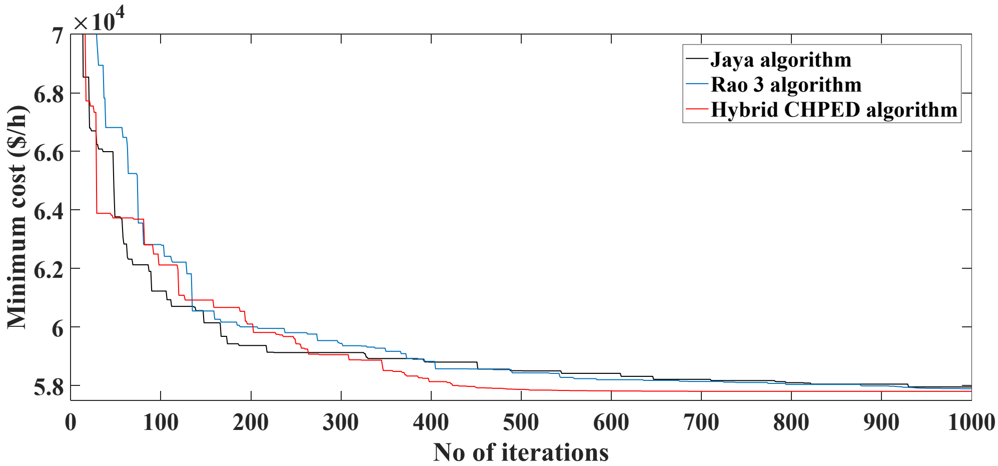

Figure 5. Minimum price convergence curve for case 2 of test system 2.

5. Conclusions and Future Scope

In this study, three different algorithms (i.e., Jaya, Rao 3, and the developed hybrid CHPED algorithm) are used for CHPED formulation. The CHPED methods are presented and used to find the optimised values of heat and power, considering VPL and POZs of thermal power units and within viable working areas of the CHP units. The results of two considered systems have shown that the developed hybrid CHPED algorithm is more effective for combined heat and power economic dispatching. The outcomes of the considered methodologies are compared with well-established methods, and it is observed that the suggested hybrid CHPED technique gives optimum results for combined heat and power dispatching.

A hybrid CHPED optimisation algorithm is developed to solve the complex problem of combined heat and power economic dispatching. There are significant improvements in the results of the hybrid CHPED algorithm in relation to the explanation quality and better convergence. The results have shown a superiority after comparing with other well-established algorithms. The exterior penalty factor method gives the desired solutions of power and heat generations in the CHPED problem.

The research study can be further enhanced by considering some other constraints of the power units. Furthermore, with the incorporation of renewable resources, such as solar and wind, the operational prices can be reduced significantly.

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Abbreviations

BA-ABC	bat algorithm artificial bee colony
BLPSO	biogeography-based learning particle swarm optimization
CHPED	combined heat and power economic dispatch
CPSO	classic particle swarm optimization
CSA	cuckoo search algorithm
CSO-PPS	civilized swarm optimization and Powell's pattern search
DE	differential evolution
EP	evolutionary programming
EMA	exchange market algorithm
FA	firefly algorithm
FSRPSO	firefly and self-regulating particle swarm optimisation
GA	genetic algorithm
GSA	gravitational search algorithm
GSO	group search optimization
HTS	heat Transfer Search
IDE	improved differential evolution
KKO	kho kho optimisation
IGA-NCM	improved genetic algorithm with novel crossover and mutation
MGSO	modified group search optimisation
MOMVO	multi-objective multi versus optimisation
OGSO	oppositional group search optimization
OTLBO	oppositional teaching learning-based optimization
POZ	prohibited operating zone
RCGA	real coded genetic algorithm
SARGA	self-adaptive real-coded genetic algorithm
TVAC-PSO	time-varying acceleration coefficients particle swarm optimization
TVAC-GSA-PSO	gravitational search algorithm particle swarm optimization time-varying acceleration coefficients
TLBO	teaching learning-based optimization
VPL	valve point loading

Appendix A

Table A1. Cost function parameters of the five-unit test system.

Power Units	$\mathbf{C_i(P_i^{TH})}$	$\mathbf{P^{TH^{max}}}$	$\mathbf{P^{TH^{min}}}$				
1	$0.000115P_1^3 + 0.00172P_1^2 + 0.6997P1 + 254.8863$	135	35				
Cogeneration Units	FOR	c	b	a	d	f	e
2	[44, 0], [44, 15.9], [40, 75], [110.2, 135.6], [125.8, 32.4], [125.8, 0]	1250	36	0.0435	0.027	0.011	0.6
3	[20, 0], [10, 40], [45, 55], [60, 0]	2650	34.5	0.1035	0.025	0.051	2.203
4	[35, 0], [35, 20], [90, 45], [90, 25], [105, 0]	1565	20	0.072	0.02	0.04	0.34
Heat unit	$h^{H^{max}}$	$h^{H^{min}}$	c	a	b		
5	2695.20	0	950	0.038	2.0109		

Table A2. Cost function parameters of the twenty-four-unit test system.

Power-Units	$\mathbf{P^{TH^{max}}}$	$\mathbf{P^{TH^{min}}}$	**c**	**b**	**a**	**e**	**f**
1	680	0	550	8.1	0.00028	300	0.035
2	360	0	309	8.1	0.00056	200	0.042
3	360	0	309	8.1	0.00056	200	0.042
4	180	60	240	7.74	0.00324	150	0.063
5	180	60	240	7.74	0.00324	150	0.063
6	180	60	240	7.74	0.00324	150	0.063
7	180	60	240	7.74	0.00324	150	0.063
8	180	60	240	7.74	0.00324	150	0.063
9	180	60	240	7.74	0.00324	150	0.063
10	120	40	126	8.6	0.00284	100	0.084
11	120	40	126	8.6	0.00284	100	0.084
12	120	55	126	8.6	0.00284	100	0.084
13	120	55	126	8.6	0.00284	100	0.084
Cogeneration Units	FOR	f	c	b	a	d	e
14	[98.8, 0], [81, 104.8], [215, 180], [247, 0]	0.031	2650	14.5	0.0345	0.03	4.2
15	[44, 0], [44, 15.9], [40, 75], [110.2, 135.6], [125.8, 32.4], [125.8, 0]	0.011	1250	36	0.0435	0.027	0.6
16	[98.8, 0], [81, 104.8], [215, 180], [247, 0]	0.031	2650	14.5	0.0345	0.03	4.2
17	[44, 0], [44, 15.9], [40, 75], [110.2, 135.6], [125.8, 32.4], [125.8, 0]	0.011	1250	36	0.0435	0.027	0.6
18	[20, 0], [10, 40], [45, 55], [60, 0]	0.051	2650	34.5	0.1035	0.025	2.203
19	[35, 0], [35, 20], [90, 45], [90, 25], [105, 0]	0.04	1565	20	0.072	0.02	2.34
Heat unit	$h^{H^{min}}$	$h^{H^{max}}$	c	b	a		
20	0	2695.2	950	2.0109	0.038		
21	0	60	950	2.0109	0.038		
22	0	60	950	2.0109	0.038		
23	0	120	480	3.0651	0.052		
24	0	120	480	3.0651	0.052		

Table A3. Prohibited operating zones of the 24-unit test system.

Test System	Unit	Zone 1, MW	Zone 2, MW	Zone 3, MW
24-Unit	1	[180, 200]	[260, 335]	[390, 420]
	2	[30, 40]	[180, 220]	[305, 335]
	3	[30, 40]	[180, 220]	[305, 335]
	10	[45, 55]	[65, 75]	-
	11	[45, 55]	[65, 75]	-

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