# Optimal Operation of Combined Heat and Power in Competitive Electricity Markets: a Case Study in IAUN

Atefeh-sadat Mirhedayati [1], Zahra Hadadi [1], Sayed-Mohammadali Zanjani [1,5]‡, Hossein Shahinzadeh [2], Ramazan Bayindir [3], Mahdi Shaneh [1,5], Jalal Moradi [4]

1- Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran.

2- Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran.

3- Electrical and Electronics Engineering, Gazi University, Ankara, Turkey.

4- Young Researchers and Elite Club, Khomeinishahr Branch, Islamic Azad University, Isfahan, Iran.

5- Smart Microgrid Research Center, Najafabad Branch, Islamic Azad University, Najafabad, Iran.

(mirhedayati.mi@sel.iaun.ac.ir, hadadi.zahra.1993@sel.iaun.ac.ir, sma_zanjani@pel.iaun.ac.ir, h.s.shahinzadeh@ieee.org, bayindir@gazi.edu.tr, m.shaneh@pel.iaun.ac.ir, sj.moradi@iaukhsh.ac.ir)

‡ Sayed-Mohammadali Zanjani; Corresponding Author, Assistant Professor, Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran, Email: sma_zanjani@pel.iaun.ac.ir

*Received: 01.04.2021 Accepted:11.06.2021*

**Abstract-** Energy efficiency management, in addition to the balance between energy supply and demand, requires thorough policy and elaborate decision-making by governments to adopt appropriate strategies to achieve the targeted goals. Combined heat and power systems featuring a decentralized and independent generation model of both electricity and heat, which procures efficient utilization of wasted energy, prevention of losses in distribution and transmission grid. Furthermore, the deployment of such a scheme results in reducing fuel consumption as well as the emission of environmental pollutants, increasing competitiveness, and liquidity in electricity markets. Optimal scheduling of small-scale combined heat and power systems in response to the consumption pattern and the electrical and heat demand of a typical customer as well as the type of interactions and interoperability with the aggregators and the market is an innovative paradigm to improve the efficiency of distributed generation resources. Due to the physical correlation between these two types of energy, the effective implementation of such schemes entails meticulous configuration and arrangement, precise modeling, and even rigorous simulation. Hence, to get a convincing and superb performance, particular attention must be paid to the model. This paper delves into the impacts of energy exchange between CHP and the upstream grid and the way to optimize it subject to satisfaction of the optimal capacity constraints. In this regard, the linear modeling method is employed and the optimization problem is solved by Grasshopper Optimization Algorithm (GOA) using MATLAB software. The Islamic Azad University of Najafabad (IAUN) complex is considered as the case study in this paper. The results imply that a significant part of the energy generated in the combined heat and power unit can be sold to the grid, this will play a vital role in reducing the cost of electricity supply.

**Keywords-** Combined Heat and Power (CHP); Energy exchange; Electricity market; Maximum profit; Grasshopper Optimization Algorithm (GOA); Energy price.

## 1. Introduction

By restructuring the power industry and the advent of power markets, the price of electricity encountered remarkable intermittencies owing to different sources of uncertainties. Moreover, the electricity price can be influenced by some other factors such as the imbalance between supply and demand, the insufficiency of transmission capacity, the fuel price fluctuations, etc [1]. With regard to the incremental demand for energy, the adoption of new approaches to control such factors and consequently the price of electricity is indispensable. One of the effective ways to manage the free capacity in the network is the deployment of distributed generation sources such as a combined heat and power (CHP) system. Besides, a considerable share of energy consumption is associated with heating and chilling systems. The heat produced in CHP systems can be used for residential and industrial purposes that boost the performance of CHP system [2]. Furthermore, nowadays, there is mounting concern about the increase in air pollution in the earth's atmosphere as well as the greenhouse effect. CHP schemes can a potential solution to alleviate this problem [3]. CHP schemes can be deployed in residential, industrial, and commercial sections. The integration of such systems, on the one hand, helps to mitigate the final price of energy for the end-users [4]. On the other hand, the optimized implementation of these schemes surges the flexibility of the grid. The optimized operation of CHP schemes highly depends on the level of electrical and thermal demand. CHP can be used for both district and local heating paradigms. It is proved that the integrated use of renewable energy sources in parallel with CHP schemes can help to implement more reliable microgrids [5]. The presence of thermal energy storage (TES) embedded in a CHP scheme can dramatically improve efficiency. This component can also improve the flexibility of CHP operation. Another merit of a CHP system is that CHP schemes can substantially reduce the distribution losses. One of the most effective solutions for effective resource management in microgrids and active distribution networks to gain the best profitability is the joint integration of TES, CHP, and electrical energy storage (ES) facilities in the form of an energy hub paradigm. In addition, electrical grids are experiencing a fast-paced transition toward smart grids. New concepts are introduced recently in the area of smart grids such as IoT, data science techniques such as data mining and deep learning, cloud computing, big data techniques, 5G communication infrastructure, etc. The incorporation of these technologies procures a smarter controlling scheme for CHP-enabled microgrids that leads to more reliable and economical operation. One of the most prominent facets of future smart grids is the more active and decisive role of demand-side resources in the operation of networks. This matter is leading to further restructuring in electricity markets and the advent of the transactive markets distribution side, in which retailers, brokers, aggregators, and consumers will actively participate based on smart contracts, specified preferences, or instantaneous desired decisions [6-8].

In [9], an economic analysis of the employment of CHP by fuel cell-based primary excitation is introduced. In this study, the thermal demand of a company is supplied and the return on investment period with respect to the electricity and heat prices. In [10], in order to start the use of an educational center, a mathematical model is described in which a gas turbine unit and a CHP unit exist in order to supply the demand of the center. In this model, even though a boiler unit is also employed, the power sale to the upstream network is not possible. In this survey, the technical constraints, as well as limitations on supply and demand, are taken into account. This model is optimized subject to supply the thermal demand and minimizing power purchasing from the market. In [11], a study is conducted to utilize a gas-fired engine along with a boiler to adjust the μCHP unit. It is assumed that there is no limit for power exchange with the main grid and the primary constraint is to satisfy thermal demand. The technical and economic restrictions are also incorporated. In [12], using economic analysis, the type and number of microturbines (as the primary μCHP exciter) required to respond to specific power and temperature curves during a sample year are discussed. Therefore, an annual profit objective function should be maximized. The operating strategy and the return period of the investment cost are also included in the model. In the paper [13], first, a CHP system with the primary exciter of a gas turbine is modeled and then the economic load dispatch and the respective mathematical formulation are presented. Finally, using GAMS software, the system performance is optimized for a daily interval. It should be noted that changes in gas turbine efficiency due to changes in ambient temperature and operation under different levels of demand have also been taken into account in the calculations. It is also assumed that the system operates in an electricity market environment. The authors in [14] discussed how μCHP systems depend on curves designed based on different electricity and heat demands per year. This article discusses how to select the type of primary exciter and the amount of rated power before the operation. Therefore, by introducing the three kinds of prime movers; Gas turbines, diesel engines, and gas engines, the model is tailored based on the consideration of environmental conditions, electric and thermal loads, fuel type, amount and price of heat, and purchase and sale prices. The operation strategy is also implemented for two models. In the first model, it is assumed that the surplus electricity is sold to the grid, and in the second model, the performance of the engine is proportional to the amount of electricity demand, and this model employed a specific technique to select the type of boiler required. The conducted study in [15] has focused on a uniaxial microturbine as the prime mover of CHP, and it delves into the techno-economic performance in comparison with the separate operation with the consideration of thermal curve. Therefore, ambient temperature and the microturbine axis speed have been introduced as two control factors. The model is also augmented by two techno-economic models. An important point in this paper is that it presents the economic model as a criterion for measuring the current net value and determine the conditions of effective operation. One of the highlights of this study is the assessment of the effectiveness of this model with respect to real electricity and heating profiles pertaining to a specific region as well as determining the maximum investment cost.

In paper [16], the operation of a microgrid including a wind turbine, solar panels, a diesel generator, a battery bank, a converter in the presence of interruptible and uninterruptible loads is modeled. This microgrid is also capable of exchanging electricity with the upstream network. The operation of this microgrid has been arranged with respect to the uncertainty of wind power generation. The operation of this microgrid is optimized with the goal of cost minimization. In [17], a multi-objective model in terms of energy, environment, and economy is designed for a CHP system under two strategies of electric power supply and heat load supply, and the results are compared to a separate generation system for an office building. The AHP method was applied to select the most appropriate mode of operation of the CHP system based on all evaluation criteria. In [18], the multi-objective optimization of a CHP is evaluated. The system consists of a gas turbine with a heat recovery boiler. In this work, exergy recovery and cost mitigation are considered as the main objectives.

Large residential or institutional complexes usually have both thermal and electric loads to a large extent. The installation of CHP schemes is a sensible suggestion for such a group of buildings. Besides, in the restructured market environment, the ability of power exchange with the upstream grid, time-based rates, pricing and clearing mechanism, and bidding strategy for the injected power to the main grid can impact the design and configuration of CHP systems. Otherwise, the size of the components will be specified wrongly. In this paper, the general insight on CHP systems is presented, and the impact of power exchange with the main grid on the configuration of the CHP scheme is investigated. The performance of the proposed method is verified by tailoring the implementation of a CHP scheme in Islamic Azad University, Najafabad branch (IAUN) as the case study.

## 2. Optimal Configuration of CHP Units

The more pervasiveness of electricity markets and restructuring in the countries with traditional structures has brought about a change in the operation of demand-side virtual power plants. For instance, CHP operation is dependent on the price of energy exchange with the main grid. In this study, in order to evaluate the role of CHP unit in an electricity market as well as the impact of the price of exchanged power on the optimal size of CHP, a simple CHP unit in an institutional complex (Islamic Azad University, Najafabad branch (IAUN)) is taken into the account.

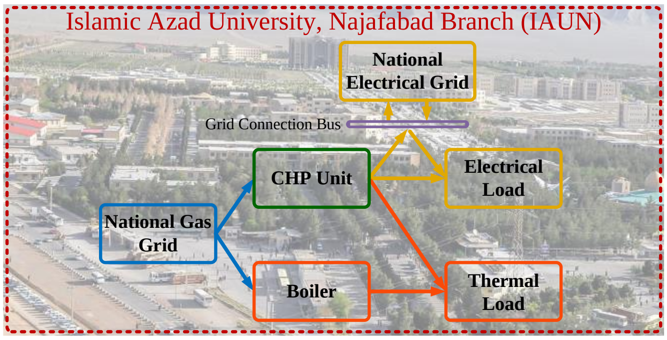


**Fig. 1.** The employed CHP scheme in IAUN institutional complex

Figure 1 demonstrates an overview of this system, which has two main components of CHP and Boiler. Such a CHP system usually contains a boiler that consumes natural gas as fuel. In order to increase the reliability in the supply of demanded power as well as to exchange electric electricity, there is a connection with the local distribution grid. In order to find the optimal size of CHP, the linear modeling approach is employed. The problem is solved by the employment of the Grasshopper Optimization Algorithm (GOA) using the MATLAB interface. As can be seen in Eq. (1), the objective function is set to minimize the investment, maintenance, and operation cost as well as the difference between the cost of energy purchasing from the main and the revenue obtained from the sale of electricity to the grid.

$$OF = min\left\{\begin{matrix} IC_{CHP,ann} + IC_{Boiler,ann} + OC_{CHP} + MC_{CHP} + \\ MC_{Boiler} + OC_{LS} + OC_{Buy} - I_{Sell} \end{matrix}\right\} \tag{1}$$

In the above, $IC$ represents the investment cost, $OC$ is the operation cost, $MC$ stands for the maintenance cost, and $OC_{LS}$ denotes the cost of load shedding, which represents the amount of power that is not supplied. $OC_{Buy}$ and $I_{Sell}$ show the cost of buy of electricity from the grid and the income obtained from the sale of electricity to the main grid [19-20]. $MC_{Boiler}$ and $MC_{CHP}$ show the maintenance costs of boiler and CHP units respectively.

### *2.1. CHP scheme modeling*

The cost per size ($/KW) index pertaining to investment for CHP technology is decreasing as the size soars. In order to model the investment cost function, the piece-wise linear approximation model is employed. In each interval, the cost per size index is considered to be fixed [21]. Hence, the annual investment cost ($IC_{CHP,ann}$) can be addressed as follows:

$$IC_{CHP,ann} = \left( \sum_{l} Size_{CHP}^{l} \times S_{CHP}^{IC(l)} \right) \times PVAF \tag{2}$$

$$Size_{CHP} = \sum_{l} Size_{CHP}^{l} \tag{3}$$

$$PVAF = \frac{(1+IR)^{n} \times IR}{(1+IR)^{n} - 1} \tag{4}$$

where $S^{IC(l)}{}_{CHP}$ and $Size^{l}{}_{CHP}$ represent the slope and the size of the $l^{th}$ piece, respectively. $Size_{CHP}$ denotes the total size of the CHP unit, which can be obtained through optimization. $PVAF$ is a factor to convert the current value to annual value [22].

The fuel cost constitutes the main part of the operation cost of CHP units. The maintenance cost is proportional to operating cost and can be considered as a fraction of operation cost. All the operation costs will be updated each year by the inclusion of the interest rate of $IR$ to the problem. The maintenance and operation cost of CHP units is given in Eq. (5).

$$OC_{CHP} + MC_{CHP} = \sum_{ymdh} P_{CHP,ymdh} \times \left( \frac{Price_{Fuel}}{HR_{Fuel} \times \eta_{CHP}} + CM_{CHP} \right) \times \frac{PVAF}{(1+IR)^{-y}} \tag{5}$$

In this equation, $P_{CHP}$ represents the output electric power of the CHP unit. $y$, $m$, $d$, $h$ stand for the indices associated with year, month, day, and hour. $Price_{Fuel}$ denotes the price of input fuel. $\eta_{CHP}$ represents the electrical efficiency of the CHP unit. $CM_{CHP}$ is the coefficient associated with the maintenance cost of the CHP unit. $HR_{Fuel}$ shows the heating value of the fuel. In addition, the output power of CHP units must be lower than the nominal capacity with respect to the availability of these units.

$$P_{CHP,ymdh} \le A_{CHP,ymdh} \times Size_{CHP} \tag{6}$$

$A_{CHP,ymdh}$ shows the state of availability of the CHP unit. When the CHP unit is on, this parameter takes the value of 1, otherwise 0. In order to calculate the output heat of CHP ($H_{CHP}$), the heat electricity ratio ($Ratio_{CHP}$) is supposed to be constant [23-25].

$$H_{CHP} = Ratio_{CHP} \times P_{CHP} \tag{7}$$

### 2.2. Boiler modeling

A boiler is responsible to supply thermal power demanded by the consumers whenever the heat produced by CHP is not sufficient. In general, the installation of a boiler incurs fewer investment costs than a CHP unit. Similarly, as the size of the boiler increases, the investment cost diminishes. The objective function of the boiler is set the same as the CHP unit [26].

### 2.3. Load balance

Equations (8) and (9) represent the necessity of thermal and electrical load balance and the criteria for a consistent supply of power.

$$P_{CHP,ymdh} + P_{Buy,ymdh} \times \eta_{PCC} + P_{LS,ymdh} = P_{Load,ymdh} + \frac{1}{\eta_{PCC}} P_{Sell,ymdh} \tag{8}$$

$$\lambda \begin{pmatrix} H_{Boiler,ymdh} + \eta_{CHPEX} \times \\ H_{CHP,ymdh} + H_{LS,ymdh} \end{pmatrix} \geq H_{Load,ymdh} \tag{9}$$

In the above equations, $P_{Load,ymdh}$ indicates the hourly load, $\eta_{PCC}$ stands for the efficiency of the internal electric grid. $P_{LS,ymdh}$ is the hourly amount of unsupplied load due to load shedding. λ denotes the efficiency of thermal pipes in the complex. $\eta_{CHPEX}$ shows the efficiency of the thermal converter of the CHP unit.

$$OC_{LS} = \sum_{ymdh} P_{LS,ymdh} \times VOLL \times \frac{PVAF}{(1+IR)^{-y}} \tag{10}$$

$$EENS = \sum_{y}\sum_{m}\sum_{d}\sum_{h} P_{LS;y,m,d,h} \leq EENS^{max} \tag{11}$$

The energy not supplied cost (*EENS*) can be obtained by the above equations, where *VOLL* is the value of lost load in hourly resolution. Equation (11) indicates that the *EENS* has to be lower than a certain sensible amount.

$$0 \leq P_{LS;y,m,d,h} \leq P_{Load;y,m,d,h} \times flage_{LS;y,m,d,h} \tag{12}$$

$$\sum_{ymdh} flage_{LS;y,m,d,h} \leq LOLE^{Max} \tag{13}$$

where $flage_{LS;y,m,d,h}$ shows a binary variable which takes a value of 1 when load shedding measure is performed, and otherwise it takes 0. Loss of load expectation (*LOLE*) index (hour/year) implies the summation of hours per year, during which the loads were unsupplied. Equation (13) conveys that *LOLE* should be lower than a certain value to ensure a certain level of reliability [27-28].

### 2.4. Availability of units

In order to find out the state of availability of each component in a CHP scheme, the Monte Carlo simulation approach is employed, in which $\lambda$ stands for the failure rate and $\mu$ shows the maintenance rate. In this method, first, a random variable is generated based on exponential distribution to define the stochastic time of $TTF_1$. Then, the component is supposed to be available within t=0 to t=$TTF_1$, which implies the value of $A_{y,m,d,h}$=1. Then, by consideration of $\mu$, the random variable of $TTR_1$ is derived from an exponential distribution that indicates the length of maintenance. Thus, the component is unavailable ($A_{y,m,d,h}$=0) during $t=TTF_1$ and $t=TTF_1+TTR_1$. This trend will continue until the end of the time horizon of the study [29-30].

## 3. Power Exchange with the Upstream Grid

It is evident that the configuration of an isolated CHP system is different from a grid-connected CHP unit. In addition, the type and size of a CHP system capable of only buying energy from the main grid differ from a system that can buy or sell electricity from and to the upstream grid in many respects. In this study, the optimal size of components is calculated in two cases of being connected or disconnected from the grid. Then the impact of power exchange with the main grid is investigated. In the case of a grid-connected CHP system, three scenarios are defined to assess the impact of price on the profitability of the CHP unit [31-33].

### 3.1. Grid-connected CHP model

The maximum exchangeable power with the main grid is restricted by the capacity of the distribution substation as well as the type of contract with the distribution system operator. CHP units have two options to sell their excess power to the grid. The first model is that if the CHP unit is capable of supplying reliable power, it can participate in the retail market or transactive distribution-side market. The second approach is to sell the electricity according to the feed-in tariff contracts, which are long-term contracts with price certainty. The former may provide better profitability, while the latter mitigates the risk of participation in a competitive market. In this study, three different scenarios for the power exchange price are taken into account.

#### 3.1.1. Scenario 1

In the first scenario, the exchange price is supposed to be fixed. Hence, the cost of buy of electricity from the upstream grid can be obtained by Eq. (14):

$$OC_{Buy} = \sum_{ymdh} \left(P_{Buy,ymdh} \times Price_{Buy,ymdh}\right) \times \frac{PVAF}{(1+IR)^{-y}} \tag{14}$$

Where $P_{Buy,ymdh}$ is the amount of power bought at interval *h*, and $Price_{Buy,ymdh}$ is the price of electricity in \$/kWh, which is remained constant in this scenario. CHP system is allowed to produce more than the demanded power of the allocated loads, and sell the surplus power to the grid with a certain fixed price provided to the grid. However, the CHP owner has to inform system operators about this amount of generation before the real-time operation. The income earned through this trade is shown by $I_{sell}$.

$$I_{Sell} = \sum_{ymdh} \left(P_{Sell,ymdh} \times Price_{Sell,ymdh}\right) \times \frac{PVAF}{(1+IR)^{-y}} \tag{15}$$

#### 3.1.2. Scenario 2

After the implementation of the Iranian targeted subsidy plan, which was a revolutionary reform in the energy sector in Iran, a new method is tailored to calculate the cost of electricity on bills consumed by different loads. In the new model, the cost of electricity is calculated in a step-wise (or levelized) format so that the customers have to pay the cost of a certain amount of electricity at each level according to the pinpointed price of that level. Figure 2 demonstrates the price of electricity based on monthly consumption.

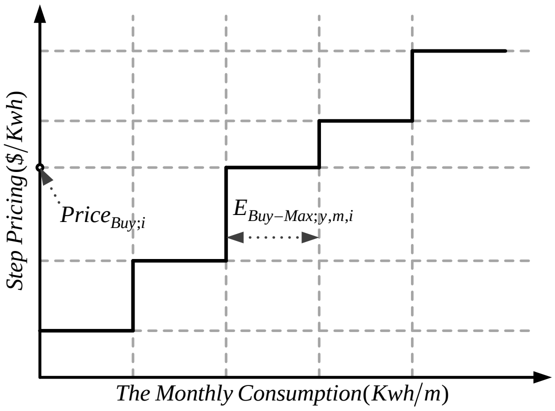


**Fig. 2.** The step-wise electricity tariffs proportional to different consumption levels

$$OC_{Buy} = \sum_{y}\sum_{m}\left(\sum_{i}\left(E_{Buy;y,m,i} \times Price_{Buy;i}\right)\right) \times \frac{PVAF}{(1+IR)^{-y}} \quad (16)$$

$$\sum_{i} E_{Buy;y,m,i} = \sum_{d}\sum_{h} P_{Buy,ymdh} \quad (17)$$

$$0 \le E_{Buy;y,m,i} \le E_{Buy-Max;y,m,i} \quad (18)$$

In these equations, $E_{Buy;y,m,i}$ represents the amount of energy bought at the $i^{th}$ step, and $Price_{Buy;i}$ stands for the price at the $i^{th}$ level.

*3.1.3. Scenario 3*

In the third scenario, the time-of-use (TOU) pricing model is incorporated. The exchange prices are supposed to be step-wise while the time of consumption affects the final cost of electricity for the consumers. The end-users face financial penalties for the consumption at peak hours while they may receive incentives for the consumption reduction. They can also be supplied by cheap tariffs at off-peak hours.

$$OC_{Buy} = \sum_{y}\sum_{m}\left(\sum_{i}\begin{pmatrix}\left(E_{Buy;y,m,i} \times Price_{Buy;i}\right) \\ +E_{Buy-P;y,m} \times \\ Price_{P} - E_{Buy-L;y,m} \times \\ Price_{L}\end{pmatrix}\right) \times \frac{PVAF}{(1+IR)^{-y}} \quad (19)$$

In the above, $P_{Buy\text{-}P;y,m}$, $P_{Buy\text{-}B;y,m}$, and $P_{Buy\text{-}L;y,m}$ represent the monthly bought power at peak, mid-peak, and off-peak hours respectively. The maximum exchangeable power with the main grid can be restricted in accordance with the capacity of the upstream substation and the items in the bilateral contract with DSO.

$$0 \le P_{Buy,ymdh} \le A_{PCC,ymdh} \times flag_{Buy,ymdh} \times P_{Buy-Max} \quad (20)$$

$$0 \le P_{Sell,ymdh} \le A_{PCC,ymdh} \times flag_{Sell,ymdh} \times P_{Sell-Max} \quad (21)$$

$$flag_{Sell,ymdh} + flag_{Buy,ymdh} \le 1 \quad (22)$$

In order to prevent the simultaneous sale and buy modes at the same interval, the binary variable of the *flag* is incorporated. $A_{PCC;ymdh}$ indicates the availability of the CHP unit at a specific interval.

*3.2. CHP model in Off-grid mode*

In this case, the capacity of the upstream grid is supposed to be zero. Hence, the CHP scheme has no power exchange with the distribution network. Thus, the variable of $A_{PCC;ymdh}$ takes the value of 0.

## 4. Grasshopper Optimization Algorithm (GOA)

Grasshopper is an insect regarded as a pest that damages plants and agricultural harvests. Grasshoppers usually live individually or in a very large swarm. The life cycle of this insect has three consecutive stages: egg, nymph, adult grasshopper. Adult grasshoppers mate and produce the eggs of the next generation. The prominent feature of the grasshopper swarm is that the swarming both nymph and adults have similar swarm behavior. The movement and jumps of nymph grasshoppers are like rolling cylinders, which is why this swarm can have migration over far distances. In the larval phase, one of the distinctive features of such a swarm is its short steps and slow movements. On the contrary, adult grasshoppers have larger steps and are able to have movement in larger distances. Seeking food sources is an inherent characteristic of all grasshoppers. Like many nature-inspired algorithms, e.g., dragonfly optimization algorithm, GOA has two main facets of exploration and exploitation. Exploration tendency indicates that the search agents are promoted to have abrupt movement, while in exploitation they tend to have local movements. These two facets are the natural behavior of grasshoppers while they are seeking new food sources that can be modeled mathematically [34].

In order to mathematically simulate GOA, the following procedure can be defined. In Eq. (23), the position of the $i^{th}$ grasshopper is represented by $X_i$. $S_i$, $G_i$, and $A_i$ are defined to model the implications of social interactions, gravity effect, and horizontal wind effect on the movement of grasshopper respectively. In order to simulate the stochastic nature of these movements, this equation can be shown as $X_i = r_1 S_i + r_2 G_i + r_3 A_i$ so that $r_1$, $r_2$, and $r_3$ are random numbers derived from the range between 0 and 1.

$$X_i = S_i + G_i + A_i \quad (23)$$

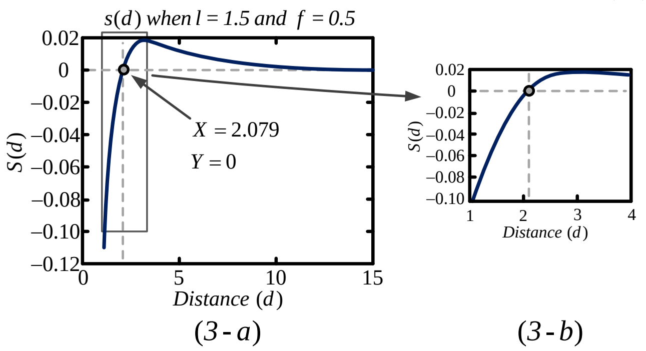


**Fig. 3.** (3.a) social force function when *l*=1.5 and *f*=0.5 (3.b) the range of social force function when *x* varies within the range of 1 to 4.

The distance between the ith and the jth grasshoppers can be explained by $d_{ij} = \left| X_j - X_i \right|$. Social force is symbolized by $s$ and can be calculated by Eq. (24). A vector from $i^{th}$ to $j^{th}$ grasshopper can be specified by $\hat{d}_{ij} = \left( X_j - X_i \right) / d_{ij}$. In Eq. (24), the intensity of attraction is shown by $f$ and the attractive length scale is presented by $l$. Besides, $N$ represents the number of individuals.

$$\begin{cases} S_i = \sum_{j=1, j \neq i}^{N} s\left(d_{ij}\right)\hat{d}_{ij} \\ s(r) = f e^{\frac{-r}{l}} - e^{-r} \end{cases} \tag{24}$$

The social force function ($s$) is shown in Fig. 3, which indicates the social interaction between grasshoppers. These interactions can be attraction or repulsion. As can be seen in Fig. 3, the distances are considered to be within 0 to 15. The coincidence point between the function $s$ takes the value of 0 and the curve can illustrate the repulsion range which is [0, 2.079]. in other words, when a grasshopper is far away from another grasshopper in its neighborhood by 2.079, it implies that there is neither repulsion nor attraction between these two. This close vicinity to this value is called comfort distance. Attraction increases between 2.079 to 4 (attraction zone) and then it gradually starts to decrease and to level off. The parameters $l$ and $f$ can considerably change the comfort zone and attraction zone. The parameter $G_i$ and $A_i$ in Eq. (23) can be calculated using Eqs. (25) and (26):

$$G_i = -g\hat{e}_g \tag{25}$$

The parameter $g$ shows the gravitational constant and $\hat{e}_g$ indicates a unity vector toward the center of the earth.

$$A_i = u\hat{e}_w \tag{26}$$

In the above, $u$ denotes a constant drift and $\hat{e}_w$ represents a vector toward the wind direction. The nymphes have no wing, which is why their movement is strongly correlated with the wind direction. Hence, by substitution of $S_i$, $G_i$, and $A_i$, Eq. (23) can be updated as follows:

$$X_i^d = c\left[ \sum_{j=1, j \neq i}^{N} c\frac{ub_d - lb_d}{2} s\left(\left|X_j^d - X_i^d\right|\right)\frac{X_j - X_i}{d_{ij}} \right] + T_d \tag{27}$$

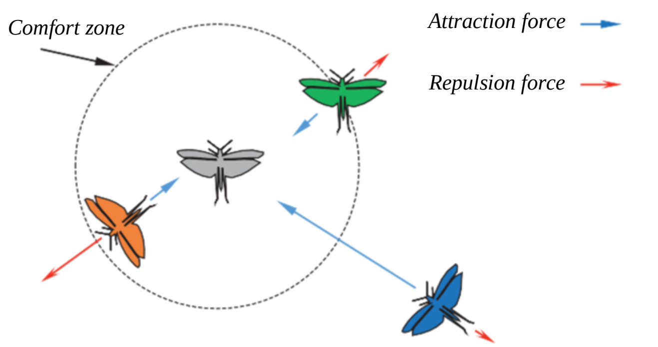


**Fig. 4.** Primitive corrective patterns between grasshoppers in a swarm

Where $ub_d$ and $lb_d$ stand for the upper and lower bound in the $D^{th}$ dimension. $T_d$ represents the best solution so far in the $D^{th}$ dimension. $c$ is constant which is assigned to reduce the comfort zone, repulsion zone, and attraction zone. In order to have balance in exploration and exploitation and to have a better convergence, the constant $c$ must be reduced as the number of iteration increases. This matter will boost the interactions between swarm members. This constant can is given in Eq. (28):

$$c = c_{max} - l\frac{c_{max} - c_{min}}{L} \tag{28}$$

In this equation, $c_{max}$ and $c_{min}$ show the maximum and minimum values of $c$, the parameter $l$ describes the current iterations, and $L$ denotes the maximum number of iterations.

The paradigm of interactions between individuals and comfort zone with respect to social force function is depicted in Fig. 4 [35].

## 5. Case Study and Numerical Modeling

In this section, the Islamic Azad University of Najafabad (IAUN) complex is considered as the case study to evaluate the effectiveness of the proposed CHP scheme. IAUN is one of the biggest universities in Iran, located in Isfahan. Figure 5 demonstrates the total heat and electric power profile of IAUN. With regard to the fact that this curve is almost the same during a month, and it usually changes at peak hours, the average load at different days of a month is considered as the load curve for that month. With respect to the historical records, the monthly load curves are shown in Fig. 6. Therefore, the monthly load curve can be obtained by the multiplication of the monthly peak value to the base-load curve. The yearly growth rate is set to 0.025 and the interest rate is supposed to be 0.30.

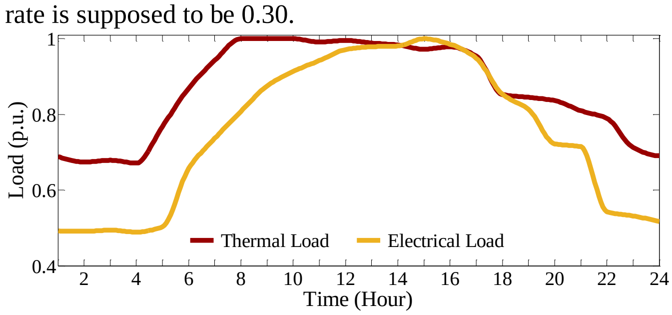


**Fig. 5.** The hourly heat and electric power load profile of IAUN in a day

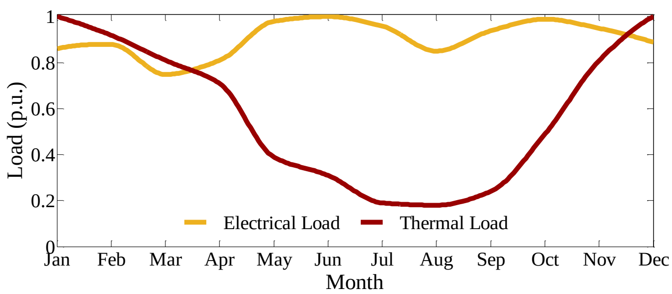


**Fig. 6.** The monthly heat and electric power load profile of IAUN in a year

The investment cost of a gas-burning CHP unit with a combustion generator joint with a boiler is illustrated in Figs. 7 and 8. With regard to the fact that gas fuel is easily available in this area, Najafabad city, this type of CHP is a very suitable choice for this scheme. The heat value of natural gas is equal to 12 kW/m$^3$. The technical parameters pertaining to the CHP unit are mentioned in Tables 1 and 2. In the first scenario, a constant price for power exchange with the main grid is considered that is equal to 0.03 $/kWh. In the second scenario, the price of sale of electricity to the network is specified to be 0.03 $/kWh, while the system operator buys electric energy from CHP unit in a step-wise model according to the prices specified in Fig. 9. In the third scenario, the TOU model is implemented. Hence, the price of electricity is increased by 0.015 $/kWh at peak hours while the price of electricity is decreased by 0.0075 $/kWh at off-peak intervals. The maximum *LOLE* and *EENS* are equal with 0.1 day/year and %0.2 of total load respectively.

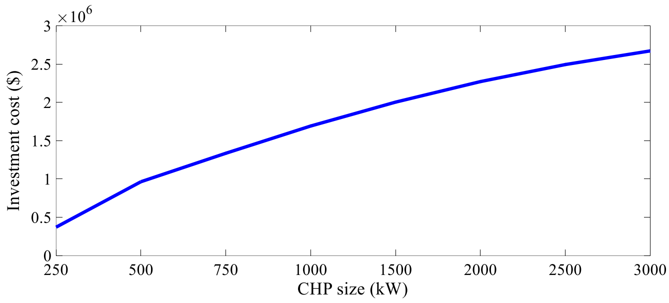


**Fig. 7.** CHP investment cost of a gas-fired combustion engine

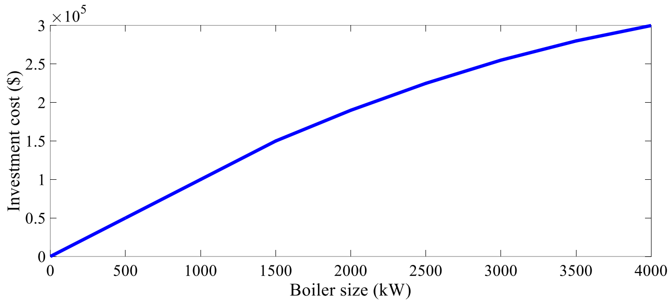


**Fig. 8.** Boiler investment cost in terms of ($)

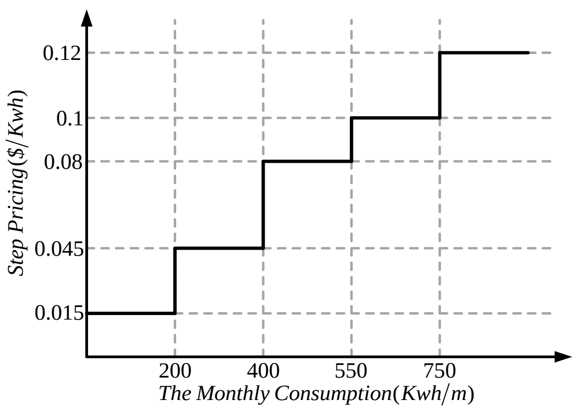


**Fig. 9.** Step-wise price of the consuming electrical power

**Table 1.** The technical parameters of the CHP unit

| Parameters | | Parameters | |
|---|---|---|---|
| $\eta_{CHPEX}$ | *0.94* | $\lambda$ | 0.96 |
| $\eta^{Boiler}$ | *0.74* | $\eta_{CHP}$ | 0.78 |
| $\eta_{PCC}$ | *0.91* | $CM_{CHP}$ | 0.01 |
| $Ratio_{CHP}$ | *1.5* | $CM_{Boiler}$ | 0.01 |

**Table 2.** The reliability parameters of the system

| Unit | FOR | RT |
|---|---|---|
| Boiler | 0.025 | 11 |
| CHP | 0.035 | 7 |
| Grid-connected | 0.01 | 5 |
| RT: Repair Time (h), FOR: Forced Outage Rate (occ./yr) | | |

The results of optimization including the optimal capacity of CHP and boiler, the energy produced by CHP, and the amount of exchanged power with the upstream network is described in Table 3 for all three scenarios.

**Table 3.** The technical parameters of the CHP unit

| | ① | Grid-connected | | |
|---|---|---|---|---|
| | | ② | ③ | ④ |
| CHP capacity (KW) | 2500 | 1898 | 1461 | 1348 |
| Boiler capacity (KW) | 2379 | 1130 | 910 | 1432 |
| The ratio of CHP electric generation to demand (%) | 96.7 | 121.03 | 109.05 | 181.01 |
| The ratio of electrical energy purchased from the grid to the demand (%) | 0 | 2.03 | 20.44 | 2.33 |
| The ratio of electrical energy sold to the grid to demand (%) | 0 | 26.07 | 32.17 | 86.34 |

*①: Isolated from grid* *②: Scenario 1*
*③: Scenario 2* *④: Scenario 3*

As the results, shown in Table 3, convey, the ability to exchange power with the main grid as well as the pricing model have prominent roles in the configuration of the CHP system. Paying less attention to these subjects may lead to underestimation or overestimation of CHP capacity. This matter can be led to financial detriments for the investor. The results of this case study imply that a remarkable share of power produced by the CHP unit, particularly in the third scenario, is sold to the network. This matter has a crucial role in the mitigation of the final price of electricity supply, which is desired by the load. It can be concluded that, with respect to the recently applied supporting policies for distributed generation in Iran as well as the surge of energy carrier prices in Iran, the incorporation of CHP units is an attractive option for the investors and large-scale loads, which are prone to install their own demand-side power source. The capacity of the connection bus between CHP and the main grid is an item that can influence and restrict the amount of power exchange with the upstream network and consequently the configuration of the CHP scheme. Hence, the capacity of the upstream substation is must be taken into consideration before tailoring a CHP scheme.

In order to evaluate the effectiveness of the optimization method, a comparison is made between GOA and some other commonly-used optimization methods. Hence, scenario 3 is solved again with various meta-heuristic approaches, and the results are compared with the results of GOA. The comparison is depicted in Fig. 10, which delineates the excellent performance of the employed model.

In general, due to the chaotic nature of exploration and exploitation models employed in GOA, it is also less probable to trap in local optimum points throughout the solution space [36]. Moreover, it leads to better results in complex non-linear, non-convex and non-smooth problems. In terms of computation burden requirements, GOA reflects convincing results. As can be easily perceived from Fig. 10, GOA has demonstrated better convergence speed in comparison with GA, PSO, MOPSO, MSFLA [37], and HBB-BC [38]. In terms of accuracy and optimality, GOA has reached better results than the rest.

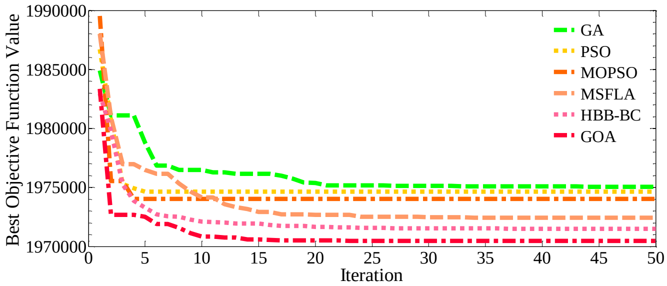


**Fig. 10.** The comparison between GOA and other powerful optimization techniques

## 6. Conclusion

Despite massive subsidies on energy carriers and the low electricity and gas tariffs in Iran, the consumption trend has always been escalating whereas the efficiency in the energy consumption sector is very low. In the current situation, the implementation of the second phase of the Iranian subsidy reform plan and updating and adjusting the price of energy carriers as close as possible to real prices can play a vital role in reducing consumption and costs of energy production and distribution. In such a condition, the utilization of CHP technology will be completely economical and sensible. This paper has examined the role of energy exchange with the main grid on the optimal capacity of the CHP unit, and then, the optimal use of the CHP system is investigated. Afterward, by taking advantage of the integration of the locust optimization algorithm (GOA), the optimal capacity of a CHP system in the Islamic Azad University of Najafabad (IAUN) is determined in order to optimize the respective objective function to supply electrical and thermal loads in different strategies. As the results of simulation and techno-economic analysis imply, a significant part of the generated energy in the CHP unit, especially in the third price-oriented scenario, is sold to the grid, which will play a prominent role in mitigating the cost of electricity supply. The capacity of the connection bus to the upstream grid is one of the limiting factors that can affect the amount of energy exchange with the network, which in turn can cause a change in the optimal configuration. Thus, it can be declared that energy-pricing policies play a decisive role in the profitability of the CHP scheme and its pervasiveness. By implementation of the Iranian subsidy reform plan and increasing the price of energy carriers, the return on capital investment for the installation of CHP systems will be faster, which inclines large loads to take advantage of this technology. The CHP capacity is directly proportional to the profitability of this unit. Besides, the investment cost for larger sizes is more economical.

## References

[1] Y. Mizuno, Y. Tanaka, F. Kurokawa and N. Matsui, "A Hospital Grid with Renewable Energy System Applied to Virtual Power Plant," *2020 8th International Conference on Smart Grid (icSmartGrid)*, 2020, pp. 203-207. IEEE.

[2] H. Shahinzadeh, J. Moradi, G. B. Gharehpetian, S. H. Fathi and M. Abedi, "Optimal Energy Scheduling for a Microgrid Encompassing DRRs and Energy Hub Paradigm Subject to Alleviate Emission and Operational Costs," *2018 Smart Grid Conference (SGC)*, 2018, pp. 1-10. IEEE.

[3] D. Arnone *et al.*, "Energy management of multi-carrier smart buildings for integrating local renewable energy systems," *2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA)*, 2016, pp. 845-850. IEEE.

[4] M. De Rosa, M. Carragher, and D. P. Finn, "Flexibility assessment of a Combined heat-power system (CHP) with energy storage under real-time energy price market framework," Thermal Science and Engineering Progress, vol. 8, pp. 426–438, 2018.

[5] M. Bornapour, R.-A. Hooshmand, A. Khodabakhshian, & M. Parastegari, "Optimal stochastic scheduling Of Chp-pemfc, WT, Pv units and hydrogen storage in reconfigurable micro grids considering reliability enhancement." *Energy Conversion and Management*, 2017, 150, 725–741.

[6] H. Shahinzadeh, J. Moradi, G. B. Gharehpetian, H. Nafisi and M. Abedi, "IoT Architecture for Smart Grids," *2019 International Conference on Protection and Automation of Power System (IPAPS)*, 2019, pp. 22-30. IEEE.

[7] J. Moradi, H. Shahinzadeh, H. Nafisi, G. B. Gharehpetian and M. Shaneh, "Blockchain, a Sustainable Solution for Cybersecurity Using Cryptocurrency for Financial Transactions in Smart Grids," *2019 24th Electrical Power Distribution Conference (EPDC)*, 2019, pp. 47-53. IEEE.

[8] G. Ala, G. Di Filippo, F. Viola, G. Giglia, A. Imburgia, P. Romano, V. Castiglia, F. Pellitteri, G. Schettino, and R. Miceli, "Different Scenarios of Electric Mobility: Current Situation and Possible Future Developments of Fuel Cell Vehicles in Italy," *Sustainability*, vol. 12, no. 2, p. 564, Jan. 2020.

[9] M. Bornapour, R. Hemmati, M. Pourbehzadi, A. Dastranj, & T. Niknam, "Probabilistic optimal coordinated planning of molten carbonate fuel cell-chp and renewable energy sources in microgrids considering hydrogen storage with point estimate method." *Energy Conversion and Management*, 2020, 206, 112495.

[10] A.E. Nezhad, F. Ghanavati, and A. Ahmarinejad, "Determining the optimal operating point of CHP units with nonconvex characteristics in the context of combined heat and power scheduling problem." *IETE Journal of Research*, 2020, pp.1-14.

[11] S. Martinez, G. Michaux, P. Salagnac, and J.L. Bouvier, "Micro-combined heat and power systems (micro-CHP) based on renewable energy sources." *Energy Conversion and Management*, 2017, *154*, pp.262-285.

[12] Y. Yang, H. Zhang, P. Yan, and K. Jermsittiparsert, "Multi-objective optimization for efficient modeling and improvement of the high temperature PEM fuel cell based Micro-CHP system." *International Journal of Hydrogen Energy*, 2020, *45*(11), pp.6970-6981.

[13] H. Hosseinnia, V. Talavat, and D. Nazarpour, "Effect of considering demand response program (DRP) in optimal configuration of combined heat and power (CHP)." *International Journal of Ambient Energy*, 2019, pp.1-6.

[14] W. Yaïci, E. Entchev and M. Longo, "Performance Analysis of Regenerative Organic Rankine Cycle System for Solar Micro Combined Heat and Power Generation Applications," *2018 7th International Conference on Renewable Energy Research and Applications (ICRERA)*, 2018, pp. 549-554. IEEE.

[15] H. Ma *et al.*, "A dispatch method of combined heat and power plants with heat storage facilities for wind power accommodation," *2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA)*, 2017, pp. 262-272. IEEE.

[16] H. Shahinzadeh, J. Moradi, G. B. Gharehpetian, M. Abedi and S. H. Hosseinian, "Multi-Objective Scheduling of CHP-Based Microgrids with Cooperation of Thermal and Electrical Storage Units in Restructured Environment," *2018 Smart Grid Conference (SGC)*, 2018, pp. 1-10. IEEE.

[17] P. Mojaver, S. Khalilarya, A. Chitsaz, and M. Assadi, "Multi-objective optimization of a power generation system based SOFC using Taguchi/AHP/TOPSIS triple method." *Sustainable Energy Technologies and Assessments*, 2020, *38*, p.100674.

[18] Y. Mizuno, Y. Tanaka, F. Kurokawa and N. Matsui, "Optimum Facility Design in Large Hospital using Renewable Energy," *2019 8th International Conference on Renewable Energy Research and Applications (ICRERA)*, 2019, pp. 712-716. IEEE.

[19] M. E. Baydokhty, A. Hajpour, & M. E. Baydokhty, "A comparison of Electricity Production Costs in far from Production Centers between CHP and Gas Power Plant Sample: Gonabad City." *Majlesi Journal of Electrical Engineering*, (2016), *10*(2).

[20] V. V. Thang, Y. Zhang, T. Ha, & S. Liu, "Optimal operation of energy hub in competitive electricity market considering uncertainties." *International Journal of Energy and Environmental Engineering*, 2018, *9*(3), 351-362.

[21] E. Mollenhauer, A. Christidis, and G. Tsatsaronis, "Evaluation of an energy-and exergy-based generic modeling approach of combined heat and power plants." *International Journal of Energy and Environmental Engineering*, 2016, *7*(2), pp.167-176.

[22] H. Al-Garni, A. Kassem, A. Awasthi, D. Komljenovic, and K. Al-Haddad, "A multicriteria decision making approach for evaluating renewable power generation sources in Saudi Arabia." *Sustainable energy technologies and assessments*, 2016, *16*, pp.137-150.

[23] J. Romdhane, H. Louahlia, & M. Marion, "Dynamic modeling of an eco-neighborhood integrated micro-CHP based on PEMFC: Performance and economic analyses." *Energy and Buildings*, 2018, *166*, 93-108.

[24] M. Sorace, M. Gandiglio, & M. Santarelli, "Modeling and techno-economic analysis of the integration of a FC-based micro-CHP system for residential application with a heat pump." *Energy*, 2017, *120*, 262-275.

[25] H. Hosseinnia, D. Nazarpour, and M.R. Benam, "Reliability Indices Utlization in Combined Heat and Power (CHP) Optimal Operation." *2014 Majlesi Journal of Electrical Engineering*, *2014*, *8*(4), pp.67-72.

[26] M. Liu, S. Wang, & J. Yan, "Operation scheduling of a coal-fired CHP station integrated with power-to-heat devices with detail CHP unit models by particle swarm optimization algorithm." *Energy*, 2021, 214, 119022.

[27] C. R. Reddy, B. S. Goud, B. N. Reddy, M. Pratyusha, C. V. Vijay Kumar and R. Rekha, "Review of Islanding Detection Parameters in Smart Grids," *2020 8th International Conference on Smart Grid (icSmartGrid)*, 2020, pp. 78-89. IEEE.

[28] S. J. A. D. Hosseini, M. Moradian, H. Shahinzadeh, & S. Ahmadi, "Optimal Placement of Distributed Generators with Regard to Reliability Assessment using Virus Colony Search Algorithm." *International Journal of Renewable Energy Research (IJRER)*, 2018, *8*(2), 714-723.

[29] S. Goud, B.L. Rao, B.N. Devi, K.S. Kumar, and N. Keerthi, "Review On Optimization Techniques Employed in Distribution Generation." *Journal of Critical Reviews*, 2020, *7*(2), pp.639-645.

[30] N. S. Bhangu, R. Singh, & G. L. Pahuja, "Availability performance analysis of thermal power plants." *2019 Journal of The Institution of Engineers (India): Series C*, *100*(3), 439-448.

[31] Ü. Çetinkaya, E. Avcı and R. Bayindir, "Time Series Clustering Analysis of Energy Consumption Data," *2020 9th International Conference on Renewable Energy Research and Application (ICRERA)*, 2020, pp. 409-413. IEEE.

[32] Y. Iwasaki, Y. Kazuto, T. Hosoe, and K. Ikeda, "Basic study for the construction of a microgrid using small wind turbines as the main power source," *2021 9th International Conference on Smart Grid (icSmartGrid)*, 2021, IEEE.

[33] M. AKIL, E. DOKUR and R. BAYINDIR, "Energy Management for EV Charging Based on Solar Energy in an Industrial Microgrid," *2020 9th International Conference on Renewable Energy Research and Application (ICRERA)*, 2020, pp. 489-493. IEEE.

[34] S. Z. Mirjalili, S. Mirjalili, S. Saremi, H. Faris, & I. Aljarah, "Grasshopper optimization algorithm for multi-objective optimization problems." *Applied Intelligence*, 2017, 48(4), 805–820.

[35] S. Saremi, S. Mirjalili, S. Mirjalili, & J. Song Dong, "Grasshopper optimization algorithm: Theory, literature review, and application in hand posture estimation." *Nature-Inspired Optimizers*, 2019, 107–122.

[36] S. Saremi, S. Mirjalili, & A. Lewis, "Grasshopper optimisation algorithm: Theory and application." *Advances in Engineering Software*, 2017, 105, 30–47.

[37] M. Moazzami, G. B. Gharehpetian, H. Shahinzadeh and S. H. Hosseinian, "Optimal locating and sizing of DG and D-STATCOM using Modified Shuffled Frog Leaping Algorithm," *2017 2nd Conference on Swarm Intelligence and Evolutionary Computation (CSIEC)*, 2017, pp. 54-59. IEEE.

[38] G. Ala, V. Castiglia, G. Di Filippo, R. Miceli, P. Romano and F. Viola, "From electric mobility to hydrogen mobility: current state and possible future expansions," *2020 IEEE 20th Mediterranean Electrotechnical Conference ( MELECON)*, 2020, pp. 1-6. IEEE.