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Optimal Energy Resource Planning and Combined Heat and Power Sizing in a Residential Area to Supply Electrical and Thermal Demand in a Reconfigured Power Grid

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Abstract

The argument of power system planning in home microgrids has become one of the burning topics in the optimization studies today among the researchers. Since the installation and use of high-capacity energy sources in power systems have many limitations and constraints, part of the perspective of power system studies tends to operate the residential micro-grids. For this purpose, in this work, operation planning is based on a residential micro-grid consisting of combined heat and power (CHP), heat storage tank, and boiler, and when possible, surplus electricity is sold to the upstream network to generate revenue. One of the innovations of this work is the use of exergy function to complete the optimization, and in practice, combine energy with economics. Other objective functions of this work are to discuss the reduction in CO2 in the air and the cost of operation. Energy management and planning in this home micro-grid is tested with different capacities and types of CHPs so that the home operator can choose the best mode to use. The multi-stage decision based dynamic programing (MSD-DP) optimization approach is used to minimize the operation costs of the proposed framework. The most important innovation of this work is the use of exergy function for energy management in a residential complex, where CHP can also be used to generate electricity and heat simultaneously. Therefore, determining the capacity of CHP and the possibility of exchanging electricity with the upstream network can be mentioned as other innovations of this research work.

Keywords: *Reconfiguration, Planning, Residential Microgrid, Optimization.*

1. Introduction

Network reconfiguration is one of the most important techniques used to achieve the goals of network operation including planning, design, service recovery, etc. but by its very nature, it is an inherently difficult issue to optimize. The main purpose of optimization and the use of its techniques are to minimize the cost functions [1]. In the case of reconfiguration per m circuit breaker, 2m solution must be considered, resulting in a large calculation volume and storage [2, 3]. The problem of real-time network reconfiguration is very difficult since the number of possible solutions is very large, and on the other hand, the problem of reconfiguration is a matter of mathematical hybrid optimization. In addition, the issue depends on the past state of each link. Since there are many problems in nature that have a discrete compositional property similar to this problem, special optimization methods have been proposed and developed to solve it but the fact that these methods have been able to solve the problem comprehensively is debatable [4]. In practice, it has been observed that rarely a solution gives a comprehensive optimal answer, and in practice, there are other limitations to be made-up; however, the undeniable point is that in any case, in any network, losses can be reduced by rearranging, loading the feeders more balanced, and other optimal goals can be achieved. Due to the extent and large number of feeders and distribution substations and observing the radial condition of distribution feeders and also other network limitations such as the capacity of transformers of the above distribution substations, allowable current and maximum acceptable voltage drop of each feeder, a higher reliability can be achieved. Nevertheless, in this work, due to the fact that the electricity network has been reconfigured, the problem of energy resource planning will be solved in such a home

micro-grid including combined heat and power (CHP), as shown in figure 1 [5].
In general, the purpose of designing and operating a micro-grid is to supply the required loads of the network. Micro-grids are small-scale and low-voltage networks, t some of which, using the CHP technology, provide heat and electrical loads to small areas such as homes, schools, universities, and commercial and economic areas [6, 7].

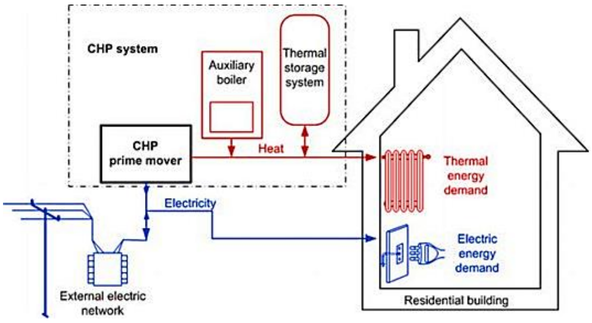

Figure 1. A home micro-grid including CHP [5].

Different loads formed at the distribution voltage level are included in the number of active distribution networks. The study of economic dispatch and operation optimization calculates the electrical quantities of the power system in steady state for the specific demands and known loads. These quantities include bus voltages, active and reactive power generated by generators, and active and reactive power flowing in transmission lines. It is not possible to achieve economic dispatch in the system without studying, and therefore, one of the most important goals of electricity companies is to generate electricity and transfer and distribute it among the consumers with a high reliability and the lowest operating costs; however, from the past until now, the issue of economic dispatch has traditionally focused on the economic issues of operation. Nowadays, with the expansion of power networks and increasing system load, combining security constraints with the concept of optimal load distribution has become an important issue.
So far, several studies have been conducted in the field of energy efficiency in energy systems. Research works have also focused on the operation planning of CHP units. However, several research gaps in this area related to the scalability, robustness assessment, and evaluation approach have never been discussed. For example, the authors in [8] have proposed a mathematical model for the cogeneration units to minimize the costs on a small scale but they do not pay attention to exergy function. In [9], a linear programming for the operation of CHP with operating constraints has been presented; however, the author ignores to take into account the power exchange with the upstream network and income analysis. In [10], the operation of a CHP unit along with a separate thermal production unit in a restructured environment has been proposed but the main research gap that is scalability has not been filled in this paper. In [11], the use of CHP along with energy storage devices has been considered. Another new research field that has been much considered by the researchers in recent years is the use of multi-carrier energy systems; however, this model does not include the exergy function and pollution analysis in a residential micro-grid. Reference [12] provides a method for the simultaneous use of CHP, photovoltaic and electrical energy storage units but the authors did not pay attention to the appropriate renewable energy sizing in a residential areas to minimize the total costs. The authors in [13] have proposed a model for energy resource planning in the presence of distributed generation sources and electric vehicles; however, the presented model did not included the exergy function to improve the system efficiency. The authors have also suggested the simultaneous use of CHP and solar panels in [14] but the sizing and pricing have been ignored in this research work. Energy management in the presence of multiple energies has also been studied in [15]; however, the main challenges of micro-grid such as scalability and robustness have not been taken into account.
Given the above explanations, this paper presents a framework that includes both the operating costs of the boiler, the CHP, and the hydrogen storage tank, as well as the exergy and CO2 reduction functions. Then considering different types of CHP, operating costs, and benefits in a home micro-grid will be studied.
This paper is organized as what follows. In the first section, the introduction to reconfiguration and the importance of energy management in the home micro-grid is discussed. The problem formulation is introduced in Section 2, and the objective functions will be analyzed. The third section describes the constraints on optimization. In Section 4, the optimization algorithm based on multi-stage decision-based dynamic programming will be presented. The simulations and case studies will be shown in Section 5, and finally, in the Section 6, we will present the conclusions.

2. Problem Formulation

As mentioned earlier, micro-power and heat generators typically have higher investment costs and lower operating costs compared to the conventional systems, which supply electricity from the grid and heat through a boiler or gas heater. Therefore, in economic evaluations, an important indicator is the total annual energy costs of the electricity and heat ($C^{TotalCHP}$) shown in equation (1). The total electricity and heat micro-generators costs include micro-power and heat initial investment costs, auxiliary boiler and heat storage source, equivalent costs related to unforeseen expected electrical and thermal energy, operating costs, the cost of purchasing electricity from the grid, the benefits of selling electricity to the grid, and the cost of maintaining the system, which form only the first objective functions of the proposed model that must be minimized.

$$F_1 = Min(C^{TotalCHP}) = Min(C^{InvCHP} + C^{InvBoiler} + C^{InvTank} + (C^{RunCHP} + C^{RunBoiler} + C^{Ele} + C^{MT} - C^{SellUtility}) \quad (1)$$

where $C^{TotalCHP}$ is the total annual energy costs of electricity and heat (\$), C^{InvCHP} is the investment cost of electricity and heat generator (\$), $C^{InvBoiler}$ is the boiler investment cost (\$), $C^{InvTank}$ is the heat storage tank investment cost (\$), C^{RunCHP} is the electricity and heat micro-generator operating cost (\$), $C^{RunBoiler}$ is the boiler operating cost (\$), C^{Ele} is the cost of purchasing electricity from the network (\$), $C^{SellUtility}$ is the economic benefits of selling electricity to the grid (\$), and C^{MT} represents the cost of repair and maintenance of micro-generators of electricity and heat and auxiliary boilers [16].

The exergetic objective function is considered as the second objective function in this modeling, which is to minimize the total initial exergy input to the system. This equation is expressed by (2).

$$F_2 = Min(EX^{In}) = (EX^{Utility} + EX^{Gas}) \quad (2)$$

where EX^{In} is the total initial exergy entering the system, $EX^{Utility}$ is the amount of electrical exergy purchased from the grid, and EX^{Gas} is the total amount of natural gas exiting in the input to the micro-generator of electricity and heat and the boiler [17].

The third part of the objective function is related to carbon emissions and its reduction. As one of the motivations for promoting the construction of micro-electric power plants and heat, excellent environmental performance, along with economic attractiveness, CO2 reduction is always expected [18]. Usually, various papers use local or global effects of carbon emissions to evaluate the environmental effects of electrical and thermal effects. In this work, since the goal is to determine the optimal capacity and strategy of optimal system performance and to promote its use for the household consumers, the amount of local CO2 emissions has been used to assess the environmental effects of electricity and heat micro-generator, as represented in equation (3).

$$F_3 = Min\ GE^{CHP} = \sum_d \sum_h (P_{d,h}^{Utility} \times CI^{ele} + P_{d,h}^{CHP} \times CI^{CHP} + H_{d,h}^{Boiler} \times CI^{Boiler}) \quad (3)$$

where GE^{CHP} is the micro-source carbon emission rate of electricity and heat (kg), $P_{d,h}^{Utiility}$ is the electric power purchased from the electricity network in the desired day and time (kWh), $P_{d,h}^{CHP}$ is the electricity generated by of electricity and heat micro-generator in the desired day and time (kWh), $H_{d,h}^{Boiler}$ is the heat produced by the boiler in the desired day and time (kWh), CI^{ele} is the grid carbon intensity (grid carbon emission rate (kg/kwh), CI^{CHP} is the carbon emission rate of the electricity and heat micro-generator (kg/kwh), and CI^{Boiler} represents the carbon emission rate of the boiler (kg/kwh).

3. Constraints

The annual investment cost of a micro- generator, auxiliary boiler, and heat storage source are described in equations (4) to (6). The investment cost of the system is calculated based on the annual investment cost. Since the investment cost is related to the entire life of the system and this model analyzes the energy costs in a sample year, the initial investment cost, which is related to the entire period of operation of the system, should be converted to an annual fixed cost statement.

$$C^{InvCHP} = Cc^{CHP} \times Cp^{RatCHP} \times \hat{k} \quad (4)$$

$$C^{InvBoiler} = Cc^{Boiler} \times Cp^{RatBoiler} \times \hat{k} \quad (5)$$

$$C^{InvTank} = Cc^{Tank} \times Cp^{RatTank} \times \hat{k}$$
$$\hat{k} = \left(\frac{I}{1-\left(\frac{1}{(1+I)^{T^{Boiler}}}\right)}\right) \tag{6}$$

where Cp^{RatCHP} is the nominal capacity of micro-electric power and heat (kW), $Cp^{RatBoiler}$ is the nominal capacity of auxiliary boiler (kW), $Cp^{RatTank}$ is the nominal capacity of heat storage source (kW), Cc^{CHP} is the electricity and heat micro-production investment cost ratio ($/kWe), Cc^{Boiler} is the boiler investment cost ratio ($/kWt), Cc^{Tank} is the Heat storage source investment cost factor ($/m3), and I is the interest rate (percentage) and operating period (year) [19-21].

The annual operating costs of the micro-electric power and heat and auxiliary boiler are also expressed in equations (7) and (8), respectively. The operating cost is calculated as the sum of costs related to fuel consumption for each period of operation of the micro-generator of electricity and heat or boiler multiplied by the price of fuel. The annual maintenance costs are also calculated as the total electricity generated by the system or the total thermal energy multiplied by a single cost factor. The cost of repairing the system is stated in equation (9).

$$C^{RunCHP} = \sum_{d}\sum_{h}\left(P_{d,h}^{CHP} \times \left(\frac{\rho_{d,h}^{Gas}}{\alpha \times HR}\right)\right) \tag{7}$$

$$C^{RunBoiler} = \sum_{d}\sum_{h}\left(H_{d,h}^{Boiler} \times \left(\frac{\rho_{d,h}^{Gas}}{\eta \times HR}\right)\right) \tag{8}$$

$$C^{MT} = \sum_{d}\sum_{h} \begin{matrix}(P_{d,h}^{CHP} \times cf^{RunCHP} + \\ H_{d,h}^{Boiler} \times cf^{RunBoiler} +) \\ H_{d,h}^{Sto} \times cf^{RunTank}\end{matrix} \tag{9}$$

where d represents the days of a year, h is the hours of a day, $\rho_{d,h}^{Gas}$ represents the consumption gas price ($/m3), cf^{RunCHP} represents the annual maintenance cost of electricity and heat micro-source (($/kWh), $cf^{RunBoiler}$ represents the boiler annual maintenance cost coefficient ($/kWh), $cf^{RunTank}$ represents the annual maintenance cost of heat storage source ($/kWh), $P_{d,h}^{CHP}$ represents the electricity generated by micro-source of electricity and heat in the desired day and hour (kWh), $H_{d,h}^{Boiler}$ represents the heat produced by the boiler in the desired day and time (kWh), $H_{d,h}^{Sto}$ represents the heat stored in the storage source (kWh), and HR represents the temperature ratio (kWh/m3). The boiler efficiency and electrical efficiency of micro-electric power and heat are η and α, respectively [22].

The cost of purchasing electricity from the grid is calculated by multiplying the amount of electricity purchased from the grid by the purchase price of electricity plus the monthly base cost. However, as we know, the purchase price of electricity from the network in different seasons of the year as well as different hours of the day and night is different, and is calculated with different tariffs.

In the discussion of electricity consumption, there are three terms: peak load, medium load, and low load. The peak time refers to the hours when the most electricity consumption occurs in the country's electricity network, and at this time, most household consumers are using electricity. Intermediate means a normal state, which is neither high nor very low power consumption during this period. Low load is also the time when the least use of electrical energy is made; these clocks are different for the first half and the second half of the year. Table 1 shows these time intervals. Table 2 shows the consumption tariffs during low-load, mid-load and peak load hours. Finally, the cost of purchasing electricity from the grid is obtained by considering the consumption time tariff from equation (10).

$$C^{Ele} = \sum_{d}\sum_{h}(E_{d,h}^{Utiility} \times \rho_{d,h}^{ele}) + \sum_{m} B_{m}^{ele} \tag{10}$$

Table 1. Light load, mid-load, and peak load hours

Months	Light load	mid-load	Peak load
From March to August	23 to 7	7 to 19	19 to 23
From September to February	22 to 6	6 to 18	18 to 22

Table 2. Electricity tariff for light load, mid-load, and peak load hours.

	Light load	mid-load	Peak load
Electricity tariff ($/kWh)	0.0436	0.0851	0.1992

In the above formula, m is the number of months in a year, $\rho_{d,h}^{ele}$ is the hourly electricity consumption tariff ($/kWh), and B_m^{ele} is the monthly base cost ($). The revenue from electricity selling to the grid is described in equation (11). This amount is obtained by multiplying the amount of electricity delivered to the network by the selling price of electricity to the network.

$$C^{SellUtility} = \sum_d \sum_h (P_{d,h}^{SellCHP} \times \rho_{d,h}^{Sell}) \tag{11}$$

where $P_{d,h}^{SellCHP}$ represents the amount of electricity generated by the micro-generator of electricity and heat that is sold to the grid (kWh), $\rho_{d,h}^{Sell}$ represents the hourly price of electricity sold to the network ($/kWh), and $E_{d,h}^{Utiility}$ is the electric power purchased from the electricity network in the desired day and time (kWh). A balance of supply and demand must be struck for heat and electricity at any point in time. In this model, the energy balance is used to prevent the impossibilities. An inequality is usually used to indicate the power balance. Equation (17) shows this equilibrium. In this equation, it is stated that the sum of electricity generated by the micro-generator of electricity and heat and the amount of electricity purchased from the grid or sold to the grid and the amount of electricity consumed by the resistor at any time equal to the sum of electric hourly charges minus the amount of uncharged electrical charge. Due to the fact that the exchange of electricity with the network is not possible at the same time and at any moment either the excess electricity is sold to the network or the electricity loss is compensated by the network, in this regard, two binary variables have been used. Since these relationships are non-linear, alternative equation (12) to (17) have been used for linearization.

$$P_{d,h}^{CHP} + (b_{d,h}^{u} \times EU_{d,h}^{Utility}) - ((1-b_{d,h}^{u}) \times PS_{d,h}^{SellCHP}) = L_{d,h}^{ele} \tag{12}$$

$$P_{d,h}^{CHP} + E_{d,h}^{Utility} - P_{d,h}^{SellCHP} = L_{d,h}^{ele} \tag{13}$$

$$0 \le E_{d,h}^{Utility} \le E^{MaxUtility} \times b_{d,h}^{u} \tag{14}$$

$$-E^{MaxUtility} \times (1-b_{d,h}^{u}) \le (E_{d,h}^{Utility} - EU_{d,h}^{Utility}) \le E^{MaxUtility} \times (1-b_{d,h}^{u}) \tag{15}$$

$$0 \le P_{d,h}^{SellCHP} \le P^{MaxSellCHP} \times (1-b_{d,h}^{u}) \tag{16}$$

$$-P^{MaxSellCHP} \times b_{d,h}^{u} \le (P_{d,h}^{SellCHP} - PS_{d,h}^{SellCHP}) \le P^{MaxSellCHP} \times b_{d,h}^{u} \tag{17}$$

In the above equations, $L_{d,h}^{ele}$ is the hourly electric charge (kWh), $b_{d,h}^{u}$ is the binary variable related to the purchase of electricity from the grid, $E^{MaxUtility}$ is the maximum capacity to supply the grid load at the point of connection of the micro-source and electricity to the grid, and $P^{MaxSellCHP}$ represents the maximum capacity to receive power at the desired point.

The thermal equilibrium of equation (18) states that the sum of the heat generated by the micro-structure of electricity and heat, the heat generated by the boiler, the heat input to the heat storage source, and the heat output from it must be equal to the instantaneous heating loads minus the unheated heat load. Since the storage source cannot be loaded and unloaded at the same time, binary variables have been used, which have caused the non-linearity of relation (18), and using relations (19) to (23), this relation is linearized.

$$H_{d,h}^{CHP} + H_{d,h}^{Boiler} + (b_{d,h}^{Discharge} \times HO_{d,h}^{Discharge}) - ((1-b_{d,h}^{Discharge}) \times HI_{d,h}^{Charge}) = (L_{d,h}^{Thermal}) \tag{18}$$

$$H_{d,h}^{CHP} + H_{d,h}^{Boiler} + H_{d,h}^{Discharge} - H_{d,h}^{Charge} = L_{d,h}^{Thermal} \tag{19}$$

$$0 \le H_{d,h}^{Charge} \le H_{d,h}^{MaxCharge} \times (1-b_{d,h}^{Discharge}) \tag{20}$$

$$-H^{MaxCharge} \times b_{d,h}^{DisCharge} \le (H_{d,h}^{Charge} - HI_{d,h}^{Charge}) \le H^{MaxCharge} \times b_{d,h}^{DisCharge} \tag{21}$$

$$0 \le H_{d,h}^{Discharge} \le H^{MaxDischarge} \times b_{d,h}^{Discharge} \tag{22}$$

$$-H^{MaxDischarge} \times (1-b_{d,h}^{Discharge}) \le (H_{d,h}^{Discharge} - HO_{d,h}^{Discharge}) \le H^{MaxDischarge} \times (1-b_{d,h}^{Discharge}) \tag{23}$$

In the above equations, $H_{d,h}^{CHP}$ is the heat generated by the micro-structure of electricity and heat (kWh), $H_{d,h}^{Boiler}$ is the heat produced by the boiler in the desired day and time (kWh), $H_{d,h}^{Discharge}$ is the thermal energy discharged from the storage tank at the desired day and time (kWh), $H_{d,h}^{Charge}$ is the thermal energy input to the heat storage source in the desired day and hour (kWh), $L_{d,h}^{Thermal}$ is the hourly heat load required for space heating and water heating (kWh), and $b_{d,h}^{Discharge}$ is the binary variables related to heat dissipation from the storage source. The parameters $H^{MaxCharge}$ and $H^{MaxDischarge}$ represent the upper limit of loading and discharging heat from the heat storage source. The performance characteristics of the electricity and heat micro-source are limited using equations (24) to (26). The constraint of equation (24) does not allow the micro-source to operate beyond its nominal capacity. equation (26) furthermore calculates the heat generated by the micro-source.

$$0 \leq P_{d,h}^{CHP} \leq Cp^{RatCHP} \tag{24}$$

$$0 \leq P_{d,h}^{SellCHP} \leq P_{d,h}^{CHP} \tag{25}$$

$$0 \leq H_{d,h}^{CHP} \leq \beta \times \frac{P_{d,h}^{CHP}}{\alpha} \tag{26}$$

In the above equations, β is the micro-thermal efficiency of the generator of electricity and heat, and $H_{d,h}^{CHP}$ represents the heat generated by the micro-source (kWh per day and hour).

4. Optimization Algorithm

The auto-regressive hybrid micro-grid system (HMGS) offers an optimal, reliable, and cost-effective solution for utilizing localized renewable energy resources over an individual DC or AC micro-grid. Generally, production, distribution, and demand subsystems are joined together to form an HMGS that vary greatly depending on the availability of renewable resources, desired services to provide, and demand subsystem parameters. These parameters together have a high impact on decision-making, reduction of the cost, and to improve the reliability of the system. The multi-stage decision-based dynamic programing (MSD-DP) optimization approach is used to minimize the operation costs of the proposed MG. In this method, for each decision stage, there are numerous system states determining the current cost. Thus the outputs of the current stage will be the input states of the next stage, as shown in figure 2.

A set of MSD formulation with the equality and non-equality constrains are formulated as below:

$$\begin{aligned} &x^{k+1} = f^k(x^k, u^k) \;\; ; \\ &x^k \epsilon X \;\; ; \;\; u^k \epsilon U \;\; ; \;\; k \epsilon \{0, 1, \dots, N-1\} \end{aligned} \tag{27}$$

$$V^N(x^N) = \min\left\{g^N(x^N) + \sum_{k=0}^{N-1} g^k(x^k, u^k)\right\} \tag{28}$$

where k donates the number of time intervals, x^k is the state vector at stage k, u^k represents the decision vector at stage k, and f^k is the state transition functions. g^k is the cost function of the state and decision variables at stage, k and V^N show the summation of costs of all N stages.

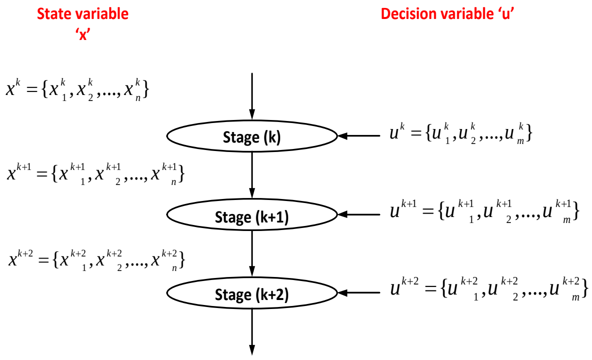

Figure 2, MSD problem tree [23, 24].

At stage k, the objective function and constraints are written in (29) and (30).

$$V^k(x^k) = \min\{g^k(x^k, u^k) + V^{k-1}(x^{k-1})\} \tag{29}$$

$$\begin{aligned} &u_{min}^{k-1} < u^{k-1} < u_{max}^{k-1} \\ &x_{min}^k < x^k < x_{max}^k \\ &x^k = f^{k-1}(x^{k-1}, u^{k-1}) \end{aligned} \tag{30}$$

where u_{min}^{k-1} and u_{max}^{k-1} are the decision variable possible range, and the state limitations are represented by x_{min}^k and x_{max}^k. The MSD problem could not be solved by itself, and therefore, the DP approach described in [23-24] is used to minimize the problem formulations, so that let X_i is considered as a state vector including the power exchanged of DGs, DR, and upstream network, and U_i is an input vector determining the real time price for operation. Briefly, the objective functions considered to be minimized in (1) to (3) is simplified as (31), and (32).

$$Z = \min\left\{\sum_{k=1}^{N-1} f_k(X_k, U_k) + f_N(X_N)\right\} \tag{31}$$

subject to:
Iterative problem solving principle:

$$x_{k+1} = g_k(x_k, u_k) \tag{32}$$

equality constraints: $h_k(x_k, u_k) = 0$
non-equality constraints: $g_k(x_k, u_k) < 0$
Equation (32) implies the all equality and non-equality relations written in (4)-(26).

5. Simulation Results

In this part of the work, two case studies with different types of CHPs are performed. The CHP specifications under study and other system inputs are given in tables 3 and 4 [25].

Table 3. Characteristics of micro-CHP ''Ecopower'' regarding ''Blauer Engel'' regulation [25].

	Ecopower	Blauer Engel
Full-load efficiency	88.9	89
Half-load efficiency	84.5	87
CO_2 (mg/Nm^3)	0.1	300
NO (mg/Nm^3)	8.4	250

Table 4. Characteristics of micro-CHP ''SOLO Stirling 161'' regarding ''Blauer Engel'' regulation [25].

	Ecopower	Blauer Engel
Full-load efficiency	98.5	89
Half-load efficiency	95.1	87
CO_2 (mg/Nm^3)	191	300
NO (mg/Nm^3)	105	250

5.1. Case study 1

In this case study, the CHP type I is used. The convergence diagram of the objective function is shown in figure 3, and shows that the total cost of planning and operation increases to about \$2.973 million. figure 4 shows the graph of changes in the annual cost of CHP in terms of its production capacity. Since the optimization problem is solved in a residential micro-grid, estimating about 2000 kW of heat does not seem too big for these areas.

Figures 5 and 6 show the graph of production capacity and load for market participants in the electricity and heating sectors, respectively. It can be seen that since these diagrams are drawn with a capacity of 0 kW for CHP, all the electrical demand is purchased from the upstream network and all the thermal power will be provided by the boiler. In this case, there is no electricity sale to the upstream network, and the revenue generation is zero.

Nonetheless if the electrical capacity of CHP is increased to 1000 kW, it is observed that according to figure 7, during the hours when the price of electricity is cheap, electricity is purchased from the upstream grid, and during the rest of the hours, CHP is almost at the rated capacity and generates power. The thermal power diagram shown in figure 8 also shows that CHP provides a large share of the power, and the boiler will supply the rest of the heat demand. In this case, the power sold to the network does not exist yet.

In the third case, we increase the electrical power capacity of CHPs to 2,000 kW. According to the diagrams shown in figures 9 and 10, the power sold to the power grid will be available, and profitability will be achieved. At this situation, the heat output is generated in such a way that a percentage of it can be stored in the tanks of the heat tank. Table 5 summarizes the profitability and investment costs in different cases.

As it can be seen in the images shown, the power sold to the upstream grid is zero for the quantities less than 1000 kW. When the capacity of CHP increases, assuming $P_{CHP} = 1500$ kW, the power sold to the upstream network is equal to 945.32 kW, and in the case of $P_{CHP} = 2000$ kW, the power sold to the upstream network will be equal to 3125.95 kW.

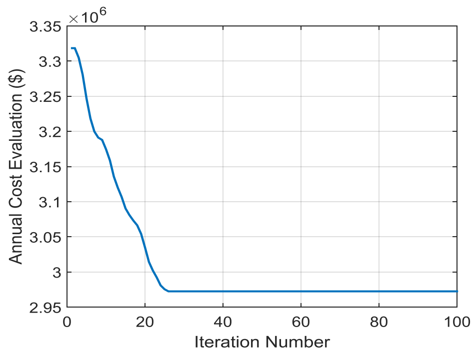

Figure 3. Convergence diagram of objective function when type I CHP is used.

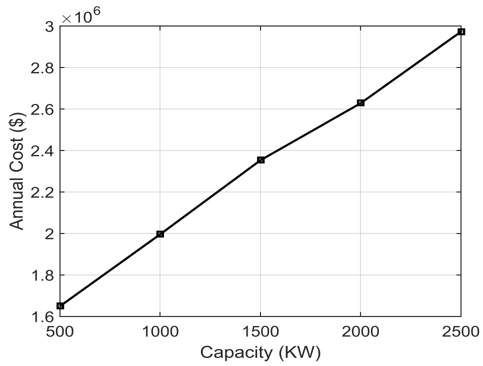

Figure 4. Annual cost of CHP in terms of its production capacity when type I CHP is used.

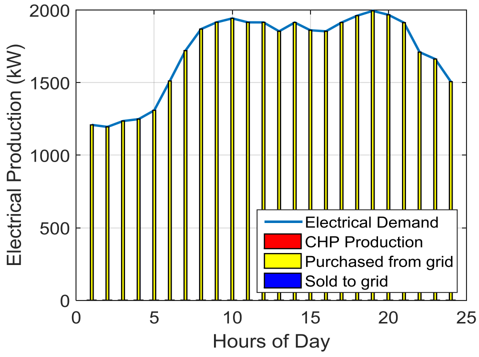

Figure 5. Electrical demand and production capacities for $P_{CHP} = 0\ kW$ when type I CHP is used.

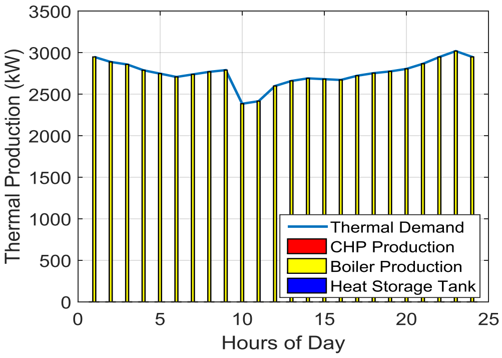

Figure 6. Thermal demand and production capacities for $P_{CHP} = 0\ kW$ when type I CHP is used.

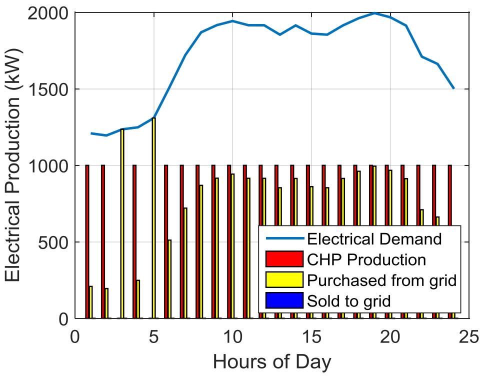

Figure 7. Electrical demand and production capacities for $P_{CHP} = 1000\ kW$ when type I CHP is used.

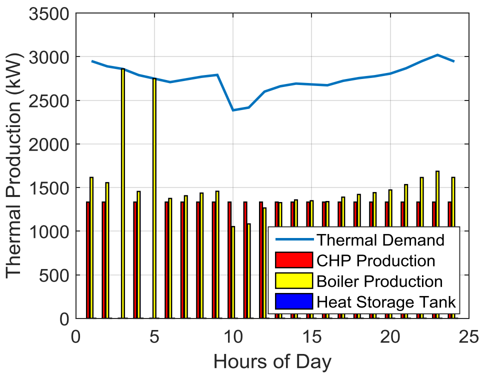

Figure 8. Thermal demand and production capacities for $P_{CHP} = 1000\ kW$ when type I CHP is used.

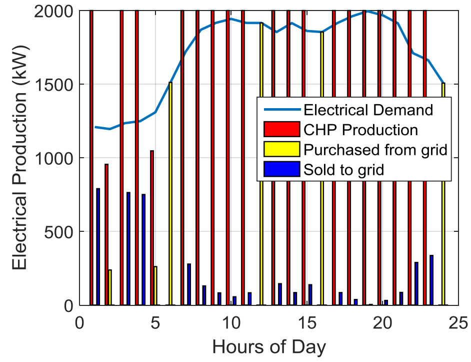

Figure 9. Electrical demand and production capacities for $P_{CHP} = 2000\ kW$ when type I CHP is used.

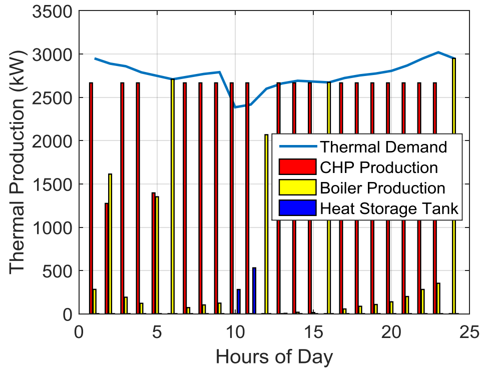

Figure 10, Thermal demand and production capacities for $P_{CHP} = 2000\ kW$ when type I CHP is used

Table 1. Costs and revenue analysis in case study 1.

P_{CHP} (kW)	Total cost ($)	Investment cost ($)	Purchase costs ($)	Revenue ($)
0	688241	0	293141	0
500	1198932	709523	233445	0
1000	1718217	1012365	145095	0
1500	2206418	1523625	83417	10227
2000	2973823	1998532	28344	57725

5.2. Case study 2

In this case study, CHP type II is used. The convergence diagram of the objective function is shown in figure 11, and shows that the total cost of planning and operation increases to about $2.662 million. Figure 12 shows the graph of changes in the annual cost of CHP in terms of its production capacity.

Similar to case study 1, figures 13 to 18 represent the amount of power generated and consumed demand for the electrical and thermal loads in proportion to the change in nominal capacity of CHP. Since the load profile is assumed to be constant in both case studies, the share of power supply in this case varies compared to the case study 1, which implies the reduced costs. Proportionally, the profit from the sale of electricity to the upstream network at the capacities more than 1500 kW has increased compared to the case study 1, which shows the high quality of CHP. Moreover, the amount of energy stored in the heat storage tank is increased by 4.7%, which indicates a higher efficiency of energy management framework presented.

As observed in the figures represented, the power sold to the upstream grid is zero for the quantities less than 1000 kW. When the capacity of CHP increases, assuming $P_{CHP} = 1500$ kW, the power sold to the upstream network is equal to 1021.56 kW, and in the case of $P_{CHP} = 2000$ kW, the power sold to the upstream network will be equal to 3265.24 kW.

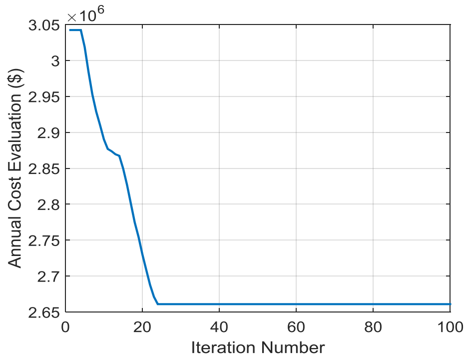

Figure 11. Convergence diagram of e objective function when type II CHP is used.

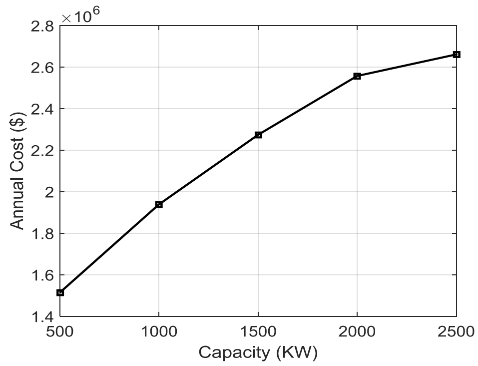

Figure 12. Annual cost of CHP in terms of its production capacity when type II CHP is used.

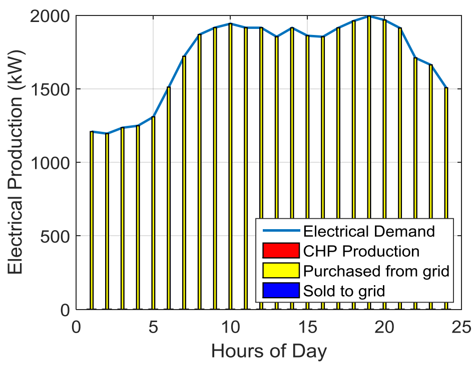

Figure 13. Electrical demand and production capacities for $P_{CHP} = 0\ kW$ when type II CHP is used.

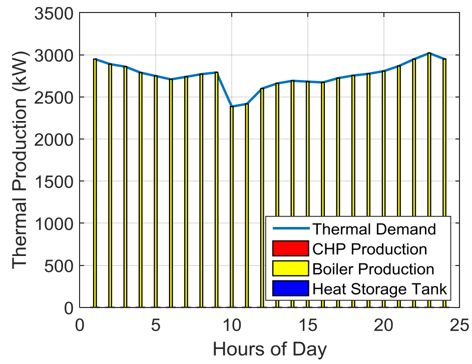

Figure 14. Thermal demand and production capacities for $P_{CHP} = 0\ kW$ when type II CHP is used.

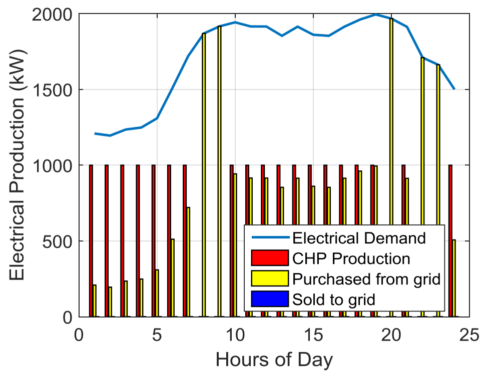

Figure 15. Electrical demand and production capacities for $P_{CHP} = 1000\ kW$ when type II CHP is used.

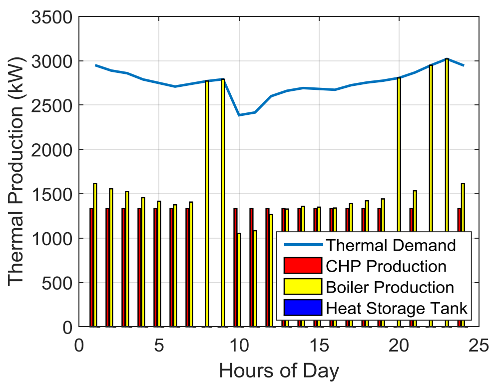

Figure 16. Thermal demand and production capacities for $P_{CHP} = 1000\ kW$ when type II CHP is used.

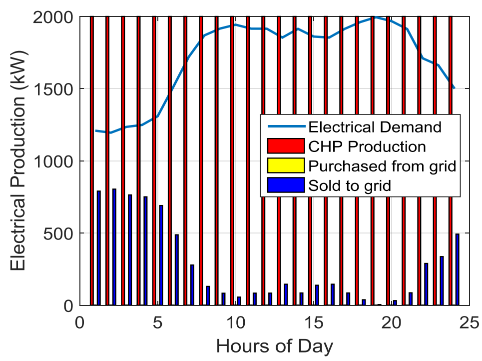

Figure 17. Electrical demand and production capacities for $P_{CHP} = 2000\ kW$ when type II CHP is used.

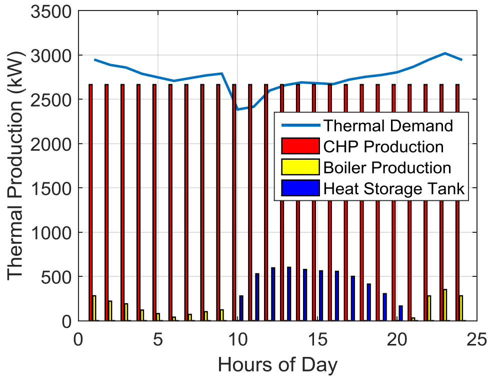

Figure 18. Thermal demand and production capacities for $P_{CHP} = 2000\ kW$ when type I CHP is used.

Table 1. Costs and revenue analysis in case study 2.

P_{CHP} (kW)	Total cost ($)	Investment cost ($)	Purchase cost ($)	Revenue ($)
0	549256	0	254326	0
500	948236	612312	201356	0
1000	1345625	983126	111302	0
1500	1958632	1312562	63152	12135
2000	2662362	1756952	12356	62354

7. Conclusion

In this work, a complete energy optimization framework with exergy function was presented, in which the capacity and profitability of a residential micro-grid were examined. The achievements of this work could be summarized as follow: 1) The use of CHP resources along with boilers and heat storage tanks provides some of the recycled heat, which can help increase the efficiency of the power grid; 2) As the capacity of the CHP system increases, the investment cost also increases, which should be taken into account in the economic feasibility studies. However, as the capacity of the system increases, so will the revenue from the sale of electricity to the upstream grid; 3) In this system, the time of use (TOU) model is used to check the electricity market price. Therefore, in the study of heat and electricity demand profiles, it is easy to implement load response programs or on-site production by increasing the capacity of CHPs; 4) The changes in the CHP model do not have much effect on the formulation of the problem of operation and cost evaluation, and only change the efficiency of CHP itself; 5) Increasing the capacity of the system from 1500 kW or upper, can be profitable for the network operator.

8. References

[1] Aziz, T., Waseem, M., Liu, S., and Lin, Z. (2022). Two-Stage MILP Model for Optimal Skeleton-Network Reconfiguration of Power System for Grid-Resilience Enhancement. Journal of Energy Engineering, 148(1), 04021060.

[2] Aziz, T., Lin, Z., Waseem, M., and Liu, S. (2021). Review on optimization methodologies in transmission network reconfiguration of power systems for grid resilience. International Transactions on Electrical Energy Systems, 31(3), e12704.

[3] Kahouli, O., Alsaif, H., Bouteraa, Y., Ben Ali, N., and Chaabene, M. (2021). Power System Reconfiguration in Distribution Network for Improving Reliability Using Genetic Algorithm and Particle Swarm Optimization. Applied Sciences, 11(7), 3092.

[4] Li, S., Wang, L., Gu, X., Zhao, H., and Sun, Y. (2022). Optimization of loop-network reconfiguration strategies to eliminate transmission line overloads in power system restoration process with wind power integration. International Journal of Electrical Power and Energy Systems, 134, 107351.

[5] Alayi, R., Seydnouri, S. R., Jahangeri, M., and Maarif, A. (2021). Optimization, Sensitivity Analysis, and Techno-Economic Evaluation of a Multi-Source System for an Urban Community: a Case Study. Renewable Energy Research and Application.

[6] Nikoukar, J., Momen, S., and Gandomkar, M. (2021). Determining the Optimal Arrangement of Distributed Generations in Microgrids to Supply the Electrical and Thermal Demands Using the Improved Shuffled Frog Leaping Algorithm. Renewable Energy Research and Applications.

[7] Beiranvand, A., Ehyaei, M. A., Ahmadi, A., and Silvaria, J. L. (2020). Energy, exergy, and economic analyses and optimization of solar organic Rankine cycle with multi-objective particle swarm algorithm. Renewable Energy Research and Application.

[8] Sun, T., Lu, J., Li, Z., Lubkeman, D. L., and Lu, N. (2017). Modeling combined heat and power systems for microgrid applications. IEEE Transactions on Smart Grid, 9(5), 4172-4180.

[9] Liu, N., Wang, J., and Wang, L. (2017). Distributed energy management for interconnected operation of combined heat and power-based microgrids with demand response. Journal of Modern Power Systems and Clean Energy, 5(3), 478-488.

[10] Nazari-Heris, M., Mohammadi-Ivatloo, B., Gharehpetian, G. B., and Shahidehpour, M. (2018). Robust short-term scheduling of integrated heat and power microgrids. IEEE Systems Journal, 13(3), 3295-3303.

[11] Misaghian, M. S., Saffari, M., Kia, M., Heidari, A., Shafie-khah, M., and Catalão, J. P. S. (2018). Tri-level optimization of industrial microgrids considering renewable energy sources, combined heat and power units, thermal and electrical storage systems. Energy, 161, 396-411.

[12] Romero-Quete, D. and Garcia, J. R. (2019). An affine arithmetic-model predictive control approach for

optimal economic dispatch of combined heat and power microgrids. Applied energy, 242, 1436-1447.

[13] Bornapour, M., Hooshmand, R. A., Khodabakhshian, A., &Parastegari, M. (2016). Optimal coordinated scheduling of combined heat and power fuel cell, wind, and photovoltaic units in micro grids considering uncertainties. Energy, 117, 176-189.

[14] Zhang, G., Cao, Y., Cao, Y., Li, D., and Wang, L. (2017). Optimal energy management for microgrids with combined heat and power (CHP) generation, energy storages, and renewable energy sources. Energies, 10(9), 1288.

[15] Wang, X., Chen, S., Zhou, Y., Wang, J., and Cui, Y. (2018). Optimal dispatch of microgrid with combined heat and power system considering environmental cost. Energies, 11(10), 2493.

[16] Iris, Ç. and Lam, J. S. L. (2021). Optimal energy management and operations planning in seaports with smart grid while harnessing renewable energy under uncertainty. Omega, 103, 102445.

[17] Naseri, A., Fazlikhani, M., Sadeghzadeh, M., Naeimi, A., Bidi, M., and Tabatabaei, S. H. (2020). Thermodynamic and exergy analyses of a novel solar-powered CO2 transcritical power cycle with recovery of cryogenic LNG using stirling engines. Renewable Energy Research and Application, 1(2), 175-185.

[18] Mirlohi, S. M., Sadeghzadeh, M., Kumar, R., and Ghassemieh, M. (2020). Implementation of a Zero-energy Building Scheme for a Hot and Dry Climate Region in Iran (a Case Study, Yazd). Renewable Energy Research and Application, 1(1), 65-74.

[19] Lai, F., Wang, S., Liu, M., and Yan, J. (2020). Operation optimization on the large-scale CHP station composed of multiple CHP units and a thermocline heat storage tank. Energy Conversion and Management, 211, 112767.

[20] Zhang, H., Zhang, Q., Gong, T., Sun, H., and Su, X. (2018). Peak load regulation and cost optimization for microgrids by installing a heat storage tank and a portable energy system. Applied Sciences, 8(4), 567.

[21] Li, Y., Sun, F., Zhang, Q., Chen, X., and Yuan, W. (2020). Numerical Simulation Study on Structure Optimization and Performance Improvement of Hot Water Storage Tank in CHP System. Energies, 13(18), 4734.

[22] Liu, M., Wang, S., and Yan, J. (2021). 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, 214, 119022.

[23] Jiang, H., Xu, L., Li, J., Hu, Z., and Ouyang, M. (2019). Energy management and component sizing for a fuel cell/battery/super-capacitor hybrid powertrain based on two-dimensional optimization algorithms. Energy, 177, 386-396.

[24] Chen, H., Zhang, Z., Guan, C., and Gao, H. (2020). Optimization of sizing and frequency control in battery/super-capacitor hybrid energy storage system for fuel cell ship. Energy, 197, 117285.

[25] Thomas, B. (2008). Benchmark testing of Micro-CHP units. Applied Thermal Engineering, 28(16), 2049-2054.