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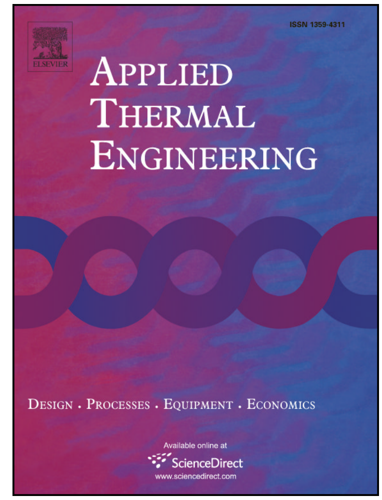

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Optimal Robust Operation of Combined Heat and Power Systems with Demand Response Programs

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Abstract

Efficiency improvement of generation units with different scales in energy systems has always been considered as an important issue. In conventional power systems, a big share of energy portfolio (40% - 60%) could be wasted since generation systems are not capable to efficiently use input energy. One solution to this problem is to incorporate combined heat and power (CHP) systems to form a multi-carrier energy hub and increase energy efficiency. In this paper, an optimization framework is developed for optimal operation of a CHP system in an uncertain environment considering demand response actions. The examined CHP-based energy system is composed of a gas turbine, heat pump, storage systems and boiler units to generate heat for space heating (SH) and domestic hot water (DHW) demands. Robust optimization framework is also employed to determine the true operating mode of CHP system (namely risk-averse, risk-neutral, or risk-taker) in the examined uncertain environment. Furthermore, a time-of-use (TOU) price-based demand response program (DRP) is used to enhance system's economic operation by changing the energy consumption pattern of end-users during the study period. Simulation results demonstrate that without DRPs, robust operation of CHP-based microgrid is obtained against 30% of more electrical load by experiencing 10.048 % more operation cost while the

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same degree of robustness is obtained by experiencing 10.019 % more operation cost considering DRPs.

Keywords: Combined heat and power system (CHP), uncertainty, robust optimization framework, demand response program (DRP).

Nomenclature

Indices

t	Time horizon index (h)

Parameters

λ_t^{net}	Hourly prices of upstream network ($/MWh)
λ^{gas}	Fixed price of gas ($/Nm^3)
η_{el}^{CHP}	Electrical efficiency of CHP unit (%)
μ_{GT}	Percentage of heat losses in gas turbine (%)
η^{B}	Combustion efficiency for boiler units (%)
η_h^{HR}	Heat recovery efficiency of boiler units (%)
$\eta_{ch}^{DHW,ST}$	Input efficiency of DHW storage (%)
$\eta_{dis}^{DHW,ST}$	Output efficiency of DHW storage (%)
$\eta_{ch}^{SH,ST}$	Input efficiency of SH storage (%)
$\eta_{dis}^{SH,ST}$	Output efficiency of SH storage (%)
$AH_{\min}^{DHW,ST}$	Minimum limitation for available heat of DHW storage (MWh)
$AH_{\max}^{DHW,ST}$	Maximum limitation for available heat of DHW storage (MWh)
$AH_{\min}^{SH,ST}$	Minimum limitation for available heat of SH storage (MWh)
$AH_{\max}^{SH,ST}$	Maximum limitation for available heat of SH storage (MWh)
COP	Coefficient of performance of the heat pump (-)
$DRP_{\max}$	Maximum limitation of consumer's participation in DRP (%)
$H_{in,\min}^{DHW,ST}$	Minimum limitation of entrant heat to the DHW storage (MW)
$H_{in,\max}^{DHW,ST}$	Maximum limitation of entrant heat to the DHW storage (MW)
$H_{in,\min}^{SH,ST}$	Minimum limitation of entrant heat to the SH storage (MW)
$H_{in,\max}^{SH,ST}$	Maximum limitation of entrant heat to the SH storage (MW)
$H_{\min}^{HP}$	Minimum limitation of output heat of heat pump (MW)
$H_{\max}^{HP}$	Maximum limitation of output heat of heat pump (MW)
LHV^{gas}	Lower heating value of gas (MWh/Nm3)
$Load_t^{EL}$	Electrical load ignoring DRP (MW)

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$Load_t^{SH}$	Space heating demand (MW)
$Load_t^{DHW}$	Domestic heat demand (MW)
M	A big constant number
$P_{\min}^{CHP}$	Minimum electricity generation of CHP units (MW)
$P_{\max}^{CHP}$	Maximum electricity generation of CHP units (MW)

Variables

$AH_t^{DHW,ST}$	Available heat of DHW storage (MWh)
$AH_t^{SH,ST}$	Available heat of SH storage (MWh)
B_t^{SH}	Binary variable; 1 if SH boiler consumes exhaust gas of gas turbine
B_t^{DHW}	Binary variable; 1 if DHW boiler consumes exhaust gas of gas turbine
$Cost$	Total operation cost of CHP-based microgrid ($)
G_t^{net}	Total purchased gas from gas network (Nm^3)
G_t^{CHP}	Total gas consumption of gas turbine (Nm^3)
G_t^{DHW}	Total gas consumption of DHW boiler (Nm^3)
G_t^{SH}	Total gas consumption of SH boiler (Nm^3)
$G_t^{CHP,EX}$	Exhaust gas of gas turbine (Nm^3)
H_t^{DHW}	Total generated heat by DHW boiler (MW)
$H_t^{DHW,D}$	Generated heat by DHW boiler through burning directly purchased gas (MW)
$H_t^{DHW,EX}$	Generated heat by DHW boiler through burning exhaust gas of gas turbine (MW)
$H_t^{DHW,L}$	Generated heat by DHW boiler to supply DHW load (MW)
$H_t^{DHW,ST}$	Generated heat by DHW boiler to charge DHW storage (MW)
H_t^{SH}	Total generated heat by DSH boiler (MW)
$H_t^{SH,D}$	Generated heat by SH boiler through burning directly purchased gas (MW)
$H_t^{SH,EX}$	Generated heat by SH boiler through burning exhaust gas of gas turbine (MW)
$H_t^{SH,L}$	Generated heat by SH boiler to supply SH load (MW)
$H_t^{SH,ST}$	Generated heat by SH boiler to charge SH storage (MW)
H_t^{HP}	Generated heat by heat pump to supply SH load (MW)
$H_{in,t}^{DHW,ST}$	Entrant heat to the DHW storage (MW)
$H_{out,t}^{DHW,ST}$	Output heat to the DHW storage (MW)
$H_{in,t}^{SH,ST}$	Entrant heat to the SH storage (MW)
$H_{out,t}^{SH,ST}$	Output heat to the SH storage (MW)
$Load_t^{EL,DRP}$	Electrical demand under DRP (MW)
P_t^{net}	Total purchased electric power from upstream network (MW)

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P_t^{CHP}	Total generated power by gas turbine of CHP unit (MW)
P_t^{HP}	Consumed electric power by heat pump to generate heat (MW)
TOU_t^{DRP}	Increased/decreased electrical load in DRP (MW)

1. Introduction

Optimal utilization of energy flows in power systems is deemed as an effective solution to reach higher energy efficiencies and lower operating costs. In this regard, optimal scheduling and planning of combined heat and power (CHP) systems, which are capable of supplying different energy demands under higher efficiencies, can be a nominated as a solution to meet the mentioned objectives [1, 2]. In addition to efficient generation, reliable operation of power system needs to be taken into account in presence of uncertainties. For example the stochastic load within a system may disturb the operation of a distribution management system (DMS) aimed to improve the energy efficiency, reliability and quality of service [2]. So, besides satisfying economic goals, uncertainty modeling and risk management is essential [3].

1.1. Literature review

In this section, a review of recent works and research activities on CHP-based energy systems is presented.

1.1.1. Uncertainty-based problems

Stochastic operation management and scheduling of CHP-based systems have been studied in various research works. For example, uncertainty-based optimal scheduling of a CHP system has been studied in [4] in which robust optimization framework has been utilized to model the uncertainty of market prices. In the same work, robust operation of the system against uncertainty is assessed. Stochastic programming method has been used to model uncertainty-based optimal operation problem of micro-CHPs in [5]. A CHP unit has been optimally

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scheduled under security constraints in presence of thermal and electrical storages in [6] in which stochastic programming has been employed to model uncertainty of load curtailment. A novel uncertainty analysis method, called modular method, has been used in [7] to study uncertainties in cost savings of a CHP system while taking various operational strategies into account. Uncertainty-based operation of a given CHP system has been studied using stochastic programming in [8, 9] in which conditional value-at-risk measure has been used to model risk-based performance. Likewise, information gap decision theory (IGDT) has been employed in [10] to model uncertainty-based optimal operation of a CHP system under uncertainty of pool market prices.

1.1.2. Optimal scheduling problems

Using a heuristic method, optimum performance and size of a CHP system have been obtained in [11]. A fuel cell generation unit has been optimally designed to be used in a CHP system using a commercial flow-sheet simulator namely ASPEN HYSYS in [12]. Non-dominated sorting genetic algorithm II (NSGA II) has been employed in [13] to optimize generation of a CHP system together with electrical and thermal storage units. Krill Herd algorithm has been implemented in [14] to solve optimal power flow problem of a CHP system while taking valve-point impact into account. Reserve market is one of field in which generation systems can participate to gain profit. Optimal operation of a CHP system has been studied subject to the opportunities provided by reserve market in [15]. Heat pump unit has been optimally designed to enhance the performance of a CHP system supplying a residential building in [16]. Non-convex optimal dispatch problem of a CHP system has been studied in [17] using real-coded genetic algorithm. Similar problem has been studied in [18] implementing group search optimizer algorithm under ranger and scrounger strategies. Sliding time window technique has been used in

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[19] to assess optimal operating point of a CHP system in presence of energy storage systems. In a like manner, optimal operation of a CHP system has been studied in [20] under demand response and different operating configurations. Scenario-based model of the problem mentioned in [20] has also been studied in [21]. Optimum dispatch problem of a CHP system has been solved in presence of heating networks and pipeline storage systems in [22]. Energy management of a CHP-based microgrid has been investigated in [23] where Lyapunov optimization approach has been employed to handle the studied NP-hard problem. In the same work, the impact of CHP unit on the economic performance of the microgrid has also been studied. The research work in [24] has elaborated on the optimal design of CHP units for district heating network, where a multi-objective optimization model has been developed in three levels to enhance economic performance of the system. A multi-objective optimization model has been developed in [25] to minimize total operation cost and emission of a given CHP-based microgrid. The proposed multi-objective model is solved by ε-constraint method and fuzzy satisfying approach under demand response services. Similarly, a multi-objective optimization model has been developed in [24] to optimize performance of a multi-energy system from economic, environmental and energy efficiency viewpoints. The results obtained in [24] reveal the positive economic and environmental impacts of multi-energy systems. Optimal scheduling of renewable-based microgrid equipped with distributed generation units such as photovoltaic units, CHP systems and electric vehicles has been investigated in [26] where shiftable loads have been modeled to participate in demand response services . In order to solve such a problem, genetic algorithm has been employed and the results demonstrate the positive impact of responsive loads on economic operation of a microgrid. Regarding the optimization aspects, different models and techniques

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have been employed in multi-energy systems. These concepts and techniques have been comprehensively studied and reviewed in [27, 28].

1.2. Novelty and contributions of this paper

In light of the previously studied research works, it can be observed that no efficient strategy is provided for managing the system operation against uncertainty. In fact, in order to take appropriate actions against uncertainties, optimal operating strategies are needed to be provided. This paper proposes an optimization framework based on robust optimization to guarantee optimal operation of a CHP system in an uncertain environment supplemented by demand response actions. Load uncertainty is modeled via a robust method in various cases and the obtained strategies are employed to ensure the risk-averse operation of the examined CHP system against uncertainty of load. In addition to provision of operating strategies against uncertainty, another key feature of the proposed optimization framework is the linearized formulations used for uncertainty modeling through robust optimization method. In fact, instead of using decomposition methods for modeling load uncertainty, a linearized mathematical model is proposed that reduces computational burden while handling uncertainties. It is noteworthy that both economic as well as uncertainty-based performances of CHP system under load uncertainty are enhanced via demand response actions. As a whole, the main contributions of the proposed framework can be expressed as follows:

- Economic operation of a CHP-based energy system is investigated under demand response concept.
- Uncertainty-based performance of the CHP system against electrical load uncertainty is ensured via robust optimization technique under a linearized mathematical model.

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- Risk-based operation of the CHP system under uncertainty is enhanced using strategies provided by robust optimization technique under demand response.

1.3. Paper organization

The rest of the paper is organized as follows: mathematical model of the proposed framework is presented in Section 2. Solution methodology based on robust optimization approach is briefly explained in Section 3. Simulation results are presented in Section 4. Finally, conclusions are presented in Section 5.

2. Problem Formulation

Optimal stable operation problem of a CHP system in an uncertain environment and in the presence of demand response concept is modeled and formulated in this section.

2.1. Objective function

Total operation cost of a CHP system (in terms of electricity procurement as well as gas procurement costs) should be minimized subject to operational constraints (1).

$$Min\, obj = Cost = \sum_{t}^{H} \left(P_t^{net} \times \lambda_t^{net} + G_t^{net} \times \lambda^{gas} \right) \tag{1}$$

Total purchased gas from gas network is composed of gas consumption of gas turbine and direct gas consumption of domestic hot water (DHW) and space heating (SH) boilers (2).

$$G_t^{net} = G_t^{CHP} + G_t^{DHW} + G_t^{SH} \tag{2}$$

2.2. Gas turbine constraints

As a key player in a CHP system, gas turbine consumes gas to generate electric power for supplying electric demand and heat pump unit. Total generated electric power by this unit is expressed by (3) and then limited by (4).

$$P_t^{CHP} = G_t^{CHP} \times \eta_{el}^{CHP} \times LHV^{gas} \tag{3}$$

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$$P_{\min}^{CHP} \le P_t^{CHP} \le P_{\max}^{CHP} \tag{4}$$

Higher efficiency of a CHP system is due to optimal utilization of energy within the structure of these systems. In fact, the exhaust gas of the gas turbines can be used to generate heat. So, this unused energy can be molded as follows (5):

$$G_t^{CHP,EX} = P_t^{CHP} \times \left(\frac{1-\eta_{el}^{CHP} - \mu_{GT}}{\eta_{el}^{CHP}} \right) \tag{5}$$

2.3. Boiler for hot water

A DHW boiler consumes gas to generate thermal energy for meeting the domestic heat demand. The gas consumed by this unit is supplied in two ways: 1) directly purchased gas from gas network 2) exhaust gas of gas turbine. Thus, generated heat by this unit can be expressed as follows:

$$H_t^{DHW} = H_t^{DHW,D} + H_t^{DHW,EX} \tag{6}$$

Generated heat is either used to supply DHW demand or charge DHW storage (7). It should be noted that total generated heat by DHW boiler should be within its rated limitation (8).

$$H_t^{DHW} = H_t^{DHW,L} + H_t^{DHW,ST} \tag{7}$$

$$H_{\min}^{DHW} \le H_t^{DHW} \le H_{\max}^{SHW} \tag{8}$$

The pattern according to which DHW boiler generates heating energy by consuming directly purchased gas from gas network and exhaust gas of a gas turbine is expressed by equations (9) and (10), respectively.

$$H_t^{DHW,D} = G_t^{DHW} \times \eta^B \times LHV^{gas} \tag{9}$$

$$H_t^{DHW,EX} = G_{DWH,t}^{CHP,EX} \times \eta_h^{HR} \tag{10}$$

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2.4. Boiler for space heating

A SH boiler directly consumes the purchased gas from gas network and exhaust gas of a gas turbine to generate heating energy for supplying space heating demand and charging SH storage system (11)-(12). It should be noted that total generated heat by SH boiler should be in its nominal range (13).

$$H_t^{SH} = H_t^{SH,D} + H_t^{SH,EX} \tag{11}$$

$$H_t^{SH} = H_t^{SH,L} + H_t^{SH,ST} \tag{12}$$

$$H_{\min}^{SH} \le H_t^{SH} \le H_{\max}^{SH} \tag{13}$$

Generated heat within two ways mentioned above is expressed by equations (14)-(15).

$$H_t^{SH,D} = G_t^{SH} \times \eta^B \times LHV^{gas} \tag{14}$$

$$H_t^{SH,EX} = G_{SH,t}^{CHP,EX} \times \eta_h^{HR} \tag{15}$$

It should be mentioned that exhaust gas of gas turbine cannot be simultaneously consumed by the DHW boiler and the SH boiler. In order to consider this point while preserving linearity for optimization, equations (16)-(19) are employed.

$$G_t^{CHP,EX} = G_{DHW,t}^{CHP,EX} + G_{SH,t}^{CHP,EX} \tag{16}$$

$$G_{DHW,t}^{CHP,EX} \le M \times B_t^{DHW} \tag{17}$$

$$G_{SH,t}^{CHP,EX} \le M \times B_t^{SH} \tag{18}$$

$$B_t^{DHW} + B_t^{SH} = 1 \tag{19}$$

2.5. Storage for hot water

Available heat in DHW storage is proportional to the heat storage in previous hour and input/output heat to/from DHW storage (20).

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$$AH_t^{DHW,ST} = AH_{t-1}^{DHW,ST} + H_{in,t}^{DHW,ST} \times \eta_{ch}^{DHW,ST} - \frac{H_{out,t}^{DHW,ST}}{\eta_{dis}^{DHW,ST}} \tag{20}$$

Limitation of available heat in DHW storage is expressed by (21).

$$AH_{\min}^{DHW,ST} \leq AH_t^{DHW,ST} \leq AH_{\max}^{DHW,ST} \tag{21}$$

Entrant heat to the DHW storage is expressed and limited by (22) and (23), respectively.

$$H_{in,t}^{DHW,ST} = H_t^{DHW,ST} \tag{22}$$

$$H_{in,\min}^{DHW,ST} \leq H_{in,t}^{DHW,ST} \leq H_{in,\max}^{DHW,ST} \tag{23}$$

2.6. Storage for space heating

Available heat inside SH storage is presented in (24) which is limited by (25).

$$AH_t^{SH,ST} = AH_{t-1}^{SH,ST} + H_{in,t}^{SH,ST} \times \eta_{ch}^{SH,ST} - \frac{H_{out,t}^{SH,ST}}{\eta_{dis}^{SH,ST}} \tag{24}$$

$$AH_{\min}^{SH,ST} \leq AH_t^{SH,ST} \leq AH_{\max}^{SH,ST} \tag{25}$$

Entrant heat to this storage is expressed by (26) and constrained by (27).

$$H_{in,t}^{SH,ST} = H_t^{SH,ST} \tag{26}$$

$$H_{in,\min}^{SH,ST} \leq H_{in,t}^{SH,ST} \leq H_{in,\max}^{SH,ST} \tag{27}$$

2.7. Heat pump constraints

Heat pump units consumes electric power provided by upstream network/gas turbine to generate thermal energy for space heating purposes. In order to satisfy the heating demand within the studied system, hot water with appropriate temperature needs to be provided. This can be achieved by using of a well-sized hot water storage tank and a heat pump. When the temperature of the water tank is below the required temperature, heat pump is operated to restore the

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temperature [29]. Generated heat pattern of a heat pump as well as its technical operating limitation are expressed by (28) and (29), respectively.

$$H_t^{HP} = P_t^{HP} \times COP \tag{28}$$

$$H_{\min}^{HP} \le H_t^{HP} \le H_{\max}^{HP} \tag{29}$$

2.8. Demand response program

Demand response concept is used in this paper to help the CHP system reduce its electrical payments by revising its electrical consumption pattern. In other words, TOU-based program is employed to shift some of the electrical energy demand from peak time intervals to off-peak ones in order to reduce CHP system operation cost [30-32]. Mathematical model of TOU-based DRP is expressed in (30)-(32). It should be noted that the mentioned DRP would not change the total energy demand (but the hourly demands) within the study period. It is also assumed that the increasing/decreasing rate of demand load at each time interval should be limited below 20 % of the hourly base load.

$$Load_t^{EL,DRP} = Load_t^{EL} + TOU_t^{DRP} \tag{30}$$

$$-DRP_{\max} \times Load_t^{EL} \le TOU_t^{DRP} \le DRP_{\max} \times Load_t^{EL} \tag{31}$$

$$\sum_t^H TOU_t^{DRP} = 0 \tag{32}$$

2.9. Energy balance constraints

Electrical demand of the CHP system which is exposed to sever uncertainty should be satisfied through the power that gas turbine generates and the power that is purchased from upstream network in the presence of DRP (33).

$$P_t^{net} + P_t^{CHP} - P_t^{HP} = Load_t^{EL,DRP} \tag{33}$$

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Generated heat by DHW boiler plus the output heat from DHW storage should satisfy DHW demand (34).

$$H_t^{DHW,L} + H_{out,t}^{DHW,ST} = Load_t^{DHW} \quad (34)$$

Produced heat by the SH boiler, generated heat by the heat pump and the heat released from SH storage should satisfy SH demand (35).

$$H_t^{SH,L} + H_t^{HP} + H_{out,t}^{SH,ST} = Load_t^{SH} \quad (35)$$

3. Solution Methodology

There are various methods for uncertainty modeling such as stochastic programming and robust optimization. In a stochastic programming approach, numerous scenarios with specific probabilities are generated for uncertain parameter and then simulations are carried out for the obtained scenarios. Based on robust optimization method, at first, an uncertainty set is defined for the system operator. This range can be variable according to the expectations of the operator. For instance, if the operator is much concerned about uncertainty, therefore a wide-range uncertainty set can be defined. After defining uncertainty set, mathematical-model based on robust optimization method is solved for the all uncertain parameters defined within the set and then results are obtained. These results are in fact operating strategies that can inform operator about possible and negative consequences of uncertainties. In short, the main feature of the robust optimization method is that it can provide the system operator with different operating schemes taking into account risk-averse, risk-neutral or risk-taker strategies against uncertainty. In this section, robust optimization approach is briefly explained [33-35].

In order to simplify explanation of the proposed approach, let's consider a simple optimization problem as follows:

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$$\underset{X_t, \forall t}{Minimize} \quad \sum_{t=1}^{H} e_t x_t \tag{36}$$

S.t

$$\sum_{t=1}^{H} a_{mt} x_t \le b_m, \quad m = 1, ..., M \tag{37}$$

$$x_t \ge 0, \quad t = 1, ..., H \tag{38}$$

$$x_t \in \{0,1\} \quad for \quad some \quad t = 1, ..., H \tag{39}$$

where, e_t is the objective function coefficient, x_t is decision variable and a_{mt}, b_m are coefficient and constant terms, respectively. In order to model robust optimization problem, the whole coefficients should be within the range $\{e_t, e_t + d_t\}$ where d_t is the deviance from coefficient e_t. Then, a new integer variable (Γ_0) is defined which value is equal to either 0 or $|J_0|$, where $|J_0|$ is the cost deviation of the objective function computed according to $J_0 = \{t \mid d_t > 0\}$. If Γ_0 is equal to $|J_0|$, cost deviations of objective function will be taken into account; otherwise ignored. Considering abovementioned explanations, mathematical model of robust optimization problem can be expressed as follows:

$$\underset{x_t, q_{ot}, y_t, \forall t; z_0}{Minimize} \quad \sum_{t=1}^{H} e_t x_t + z_0 \Gamma_0 + \sum_{t=1}^{H} q_{ot} \tag{40}$$

S.t.

Eqs. (37)-(39) (41)

Applying dual method presented in [36], new mathematical model of robust optimization problem can be expressed as follows:

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$$\underset{x_t, q_{ot}, y_t, \forall t; z_0}{Minimize} \quad \sum_{t=1}^{H} e_t x_t + z_0 \Gamma_0 + \sum_{t=1}^{H} q_{ot} \tag{42}$$

S.t.

$$\text{Eqs. (37)-(39)} \tag{43}$$

$$z_0 + q_{ot} \geq d_t y_t, \quad t = 1, ..., H \tag{44}$$

$$q_{ot} \geq 0, \quad t = 1, ..., H \tag{45}$$

$$y_t \geq 0, \quad t = 1, ..., H \tag{46}$$

$$z_0 \geq 0 \tag{47}$$

$$x_t \leq y_t, \quad t = 1, ..., H \tag{48}$$

It should be noticed that z_0 and q_{ot} are dual variables of the standard problem. Accordingly, the proposed robust optimization model for optimal operation of CHP system within uncertainty of electrical demand under DRP can be expressed as follows:

$$Min\, obj = Cost = \left(\sum_{t}^{H} \left(P_t^{net} \times \lambda_t^{net} + G_t^{net} \times \lambda^{gas} \right) + z_0 \Gamma_0 + \sum_{t=1}^{H} q_{ot} \right) \tag{49}$$

s.t.

$$\text{Eqs. (2)-(35) \& (44)-(47)} \tag{50}$$

$$\lambda_t^{net} \leq y_t, \quad t = 1, ..., H \tag{51}$$

4. Numerical study

In this section, simulation data and results related to the optimal robust operation problem of a CHP-based demand-response-driven microgrid in an uncertain environment is presented. The examined system is related to a large hotel located in Beijing with an area of 30,000 m^2. In the studied system illustrated in Fig. 1, two types of energy units are utilized: the first type is the prime mover (such as the gas turbine) which converts input fuel into heat and/or electricity. The

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second type is the energy converter (such as boilers and heat pumps) that converts the produced heat and/or electricity by the prime movers into thermal energy to be used by the end-use consumers (SH and DHW demands [29, 37, 38]).

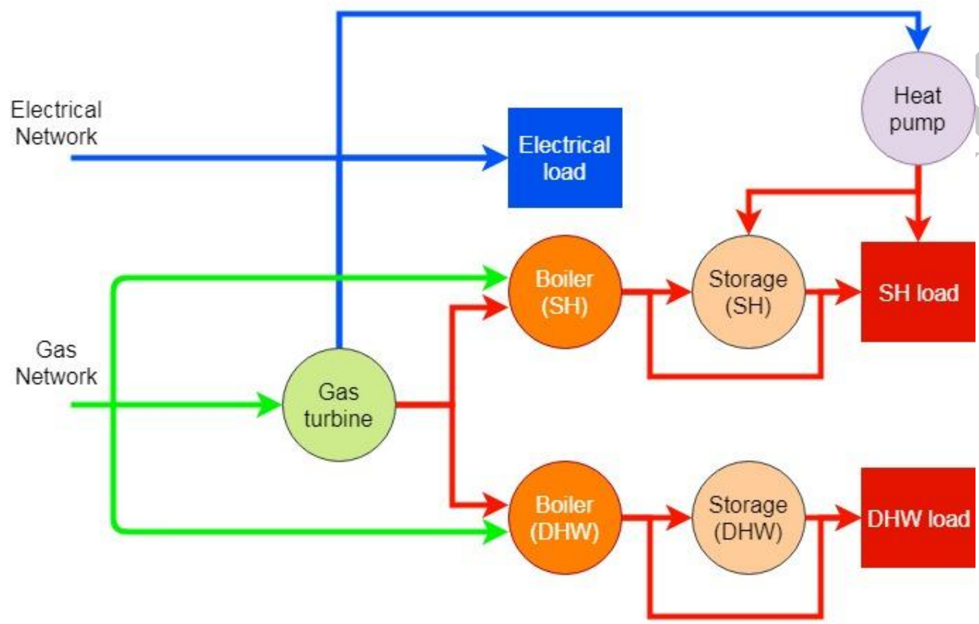

Fig. 1. Sample studied system [38]

4.1. Input data

In this section, necessary input information and data is presented. Hourly price of electricity is illustrated in Fig. 2.

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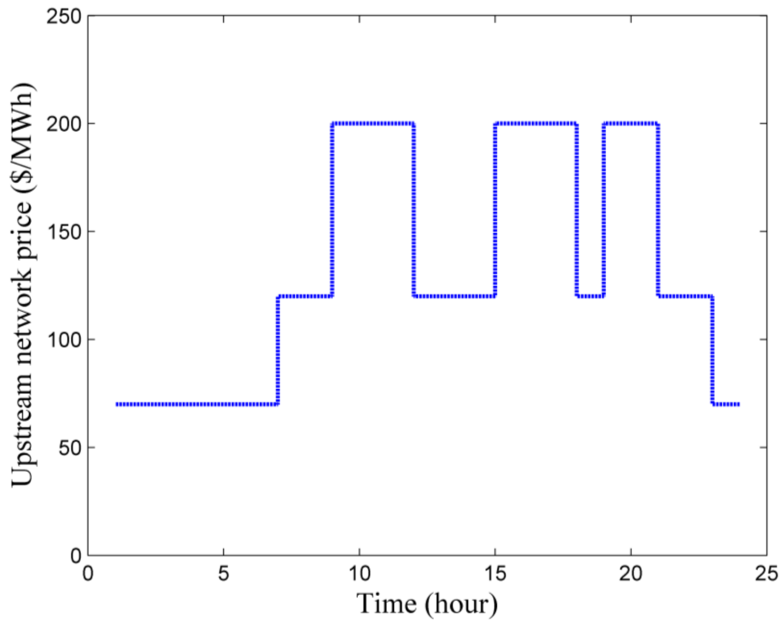

Fig. 2. Hourly upstream network prices [38]

Hourly electrical demand for a typical day in winter in its three possible levels including upper, mid and lower levels is shown in Fig. 3. Forecasted profile of energy demands for typical days in summer and transitional seasons are also illustrated in Figs 4 and 5, respectively.

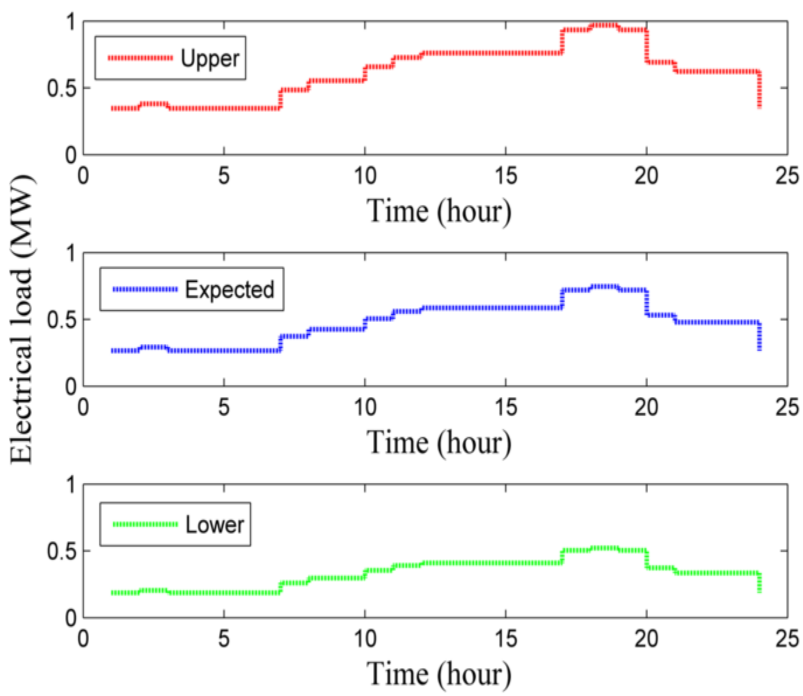

Fig. 3. Electrical demand in winter [38]

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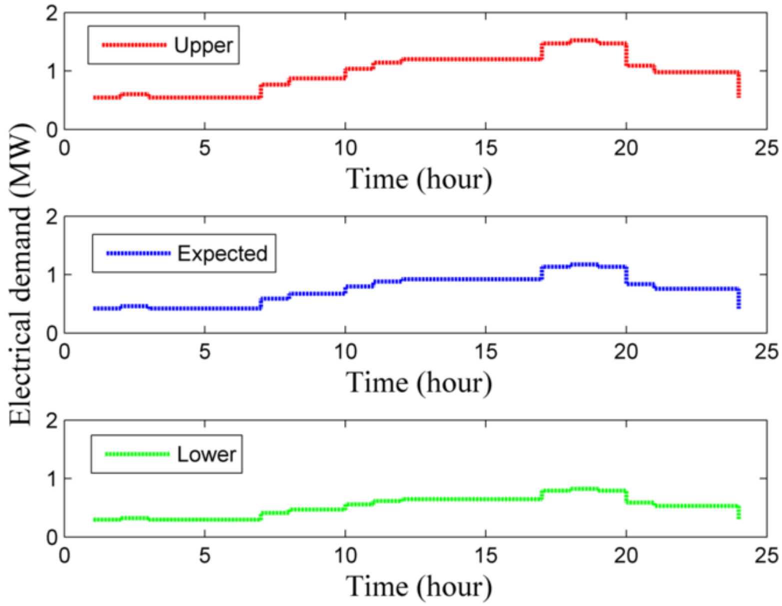

Fig. 4. Electrical demand in summer [37]

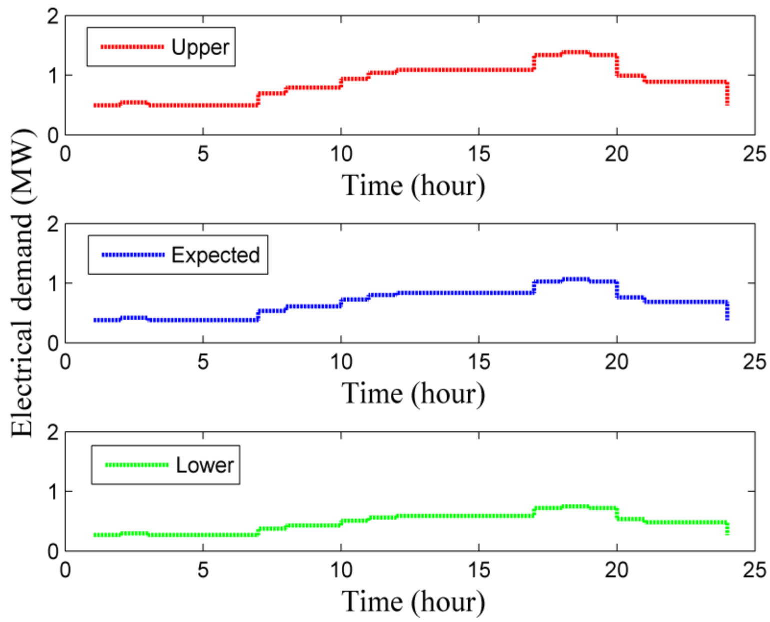

Fig. 5. Electrical demand in transitional seasons [37]

Hourly profiles of domestic hot water and space heating demands for a typical day in winter, summer and transitional seasons are also depicted in Figs. 6-8, respectively.

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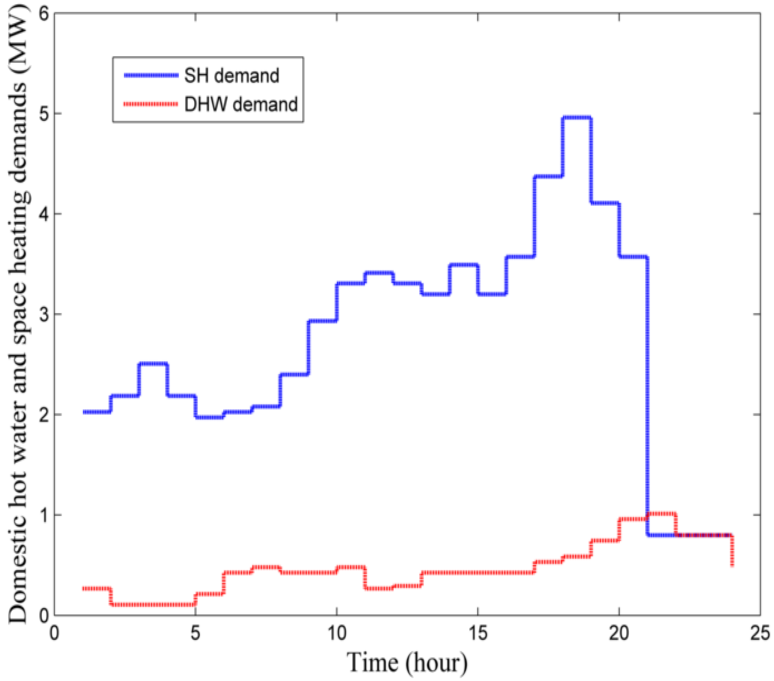

Fig. 6. Domestic hot water and space heating demands in winter [38]

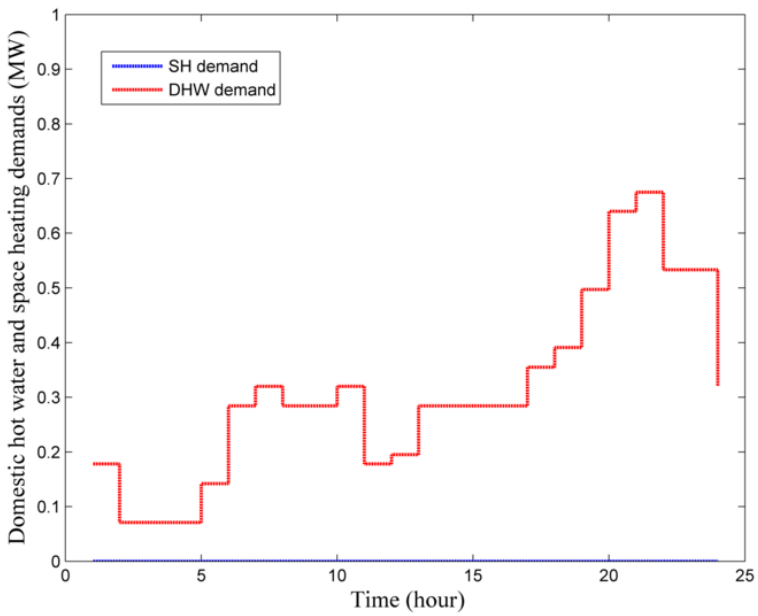

Fig. 7. Domestic hot water and space heating demands in summer [37]

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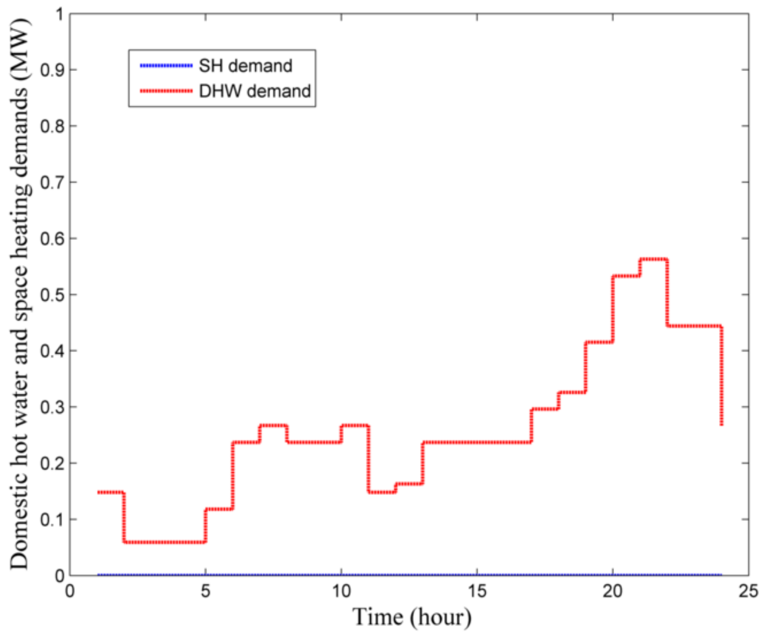

Fig. 8. Domestic hot water and space heating demands in transitional seasons [37]

Technical data related to heat pump unit, gas turbine and boiler is presented in Table 1.

Table 1: Technical info of heat pump unit, gas turbine and boiler units [29, 38]

Gas turbine	value	Unit	Boiler	value	Unit	Heat pump	value	Unit
η_{el}^{CHP}	24	%	η^{B}	90	%	COP	3	-
μ_{GT}	32	%	η_{h}^{HR}	80	%	$H_{\min}^{HP}$	0	MW
M	200	-	$H_{\min}^{DHW}$	0	MW	$H_{\max}^{HP}$	3	MW
$P_{\min}^{CHP}$	0	MW	$H_{\max}^{SH}$	5	MW	-	-	
$P_{\max}^{CHP}$	1.25	MW	$H_{\min}^{SH}$	0	MW	-	-	
LHV^{gas}	0.01	MWh/Nm3	$H_{\max}^{SH}$	1	MW	-	-	

Finally, technical parameters related to both DHW and SH storages are presented in Table 2.

Table 2: Technical info of DHW and SH storage systems [29, 38]

DHW storage	value	Unit	DHW storage	value	Unit
$\eta_{ch}^{DHW,ST}$	90	%	$\eta_{ch}^{SH,ST}$	90	%
$\eta_{dis}^{DHW,ST}$	90	%	$\eta_{dis}^{SH,ST}$	90	%

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$AH_{\min}^{DHW,ST}$	0	MWh	$AH_{\min}^{SH,ST}$	0	MWh
$AH_{\max}^{DHW,ST}$	0.3	MWh	$AH_{\max}^{SH,ST}$	1	MWh
$H_{in,\min}^{DHW,ST}$	0	MW	$H_{in,\min}^{SH,ST}$	0	MW
$H_{in,\max}^{DHW,ST}$	0.3	MW	$H_{in,\max}^{SH,ST}$	1	MW

Approximate annual energy consumptions of the studied test system is presented in Table 3 [37].

Table 3: Estimated annual energy consumptions

Season	Summer season	Transitional seasons	Winter season
Electrical demand (MWh)	1647.600	2915.108	1014.651
SH demand (MWh)	0	0	5762.403
DHW demand (MWh)	695.628	1128.214	1009.783

Gas price is considered as 0.38 $/Nm^3 [38]. Simulations have been conducted on general algebraic modeling system (GAMS) [39] under a mixed-integer linear programming.

4.2. Simulation results

Results related to simulation of robust operation of the proposed CHP system are presented in this section.

4.2.1. Winter

Figure 5, shows the electrical demand after incorporating DRP. As can be observed, the load has been shifted from peak-time intervals to off-peak ones to reduce system’s cost within different load levels. Under uncertainty of load, three scenarios are expected: 1) load increases beyond the expected value (upper level), 2) load remains unchanged (expected level), 3) load decreases below the expected level (lower level).

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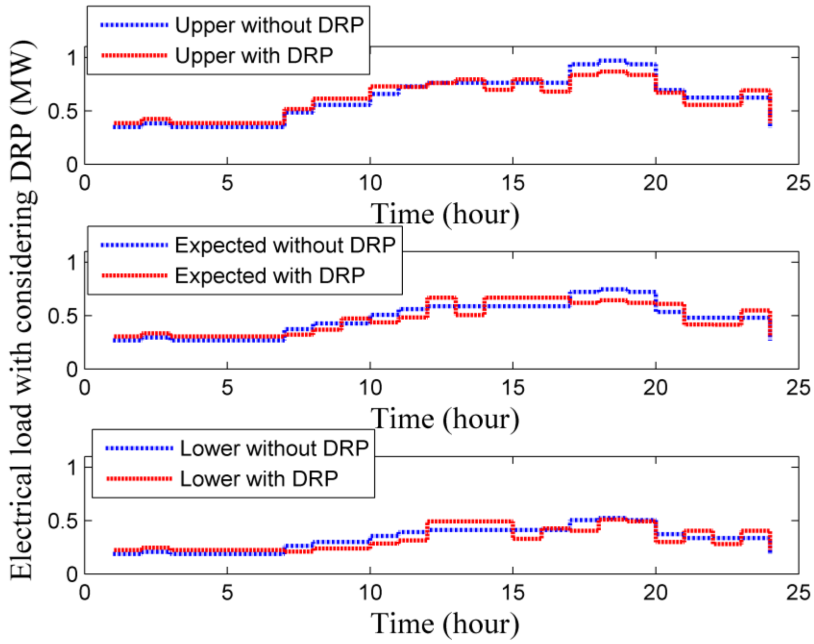

Fig. 6. Electrical load with DRP in a typical day in winter

Operation cost of CHP system within the uncertainty set in a typical day in winter is presented without/with DRP in 11 iterations in Fig. 7. The load is increased within the iterations from the minimum value up to the maximum value. So, the first iteration is related to the minimum robust condition in which the load value is the possible minimum. The 5th iteration is related to the base condition or so called mid-robust condition and the 11th iteration is related to the maximum robust condition.

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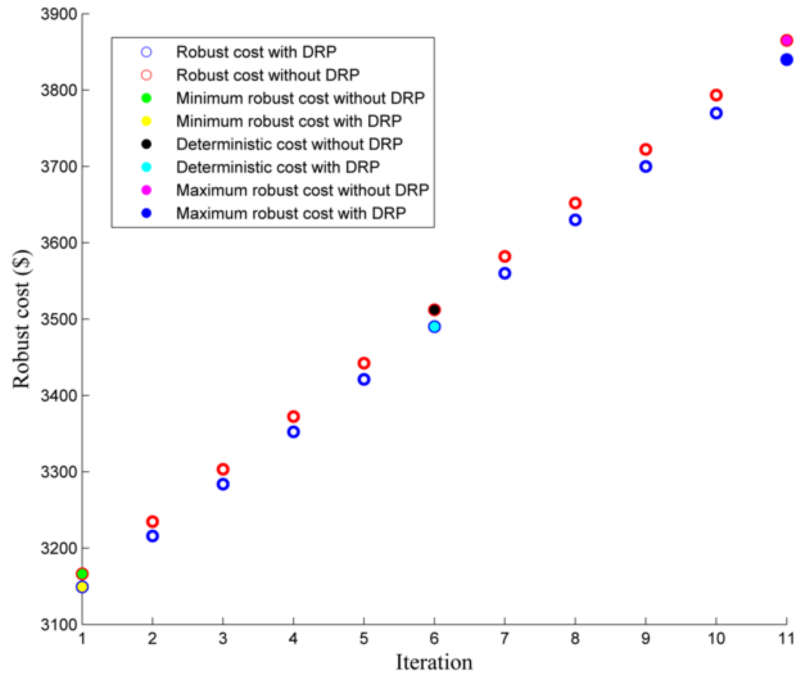

Fig. 7. Robust cost without/with DRP in a typical day in winter

As it is illustrated above, total operation cost of CHP system without DRP in the maximum, mid and minimum robust conditions is $ 3865.144, $ 3512.218 and $ 3166.440, respectively. In fact, CHP system has to pay 10.048 % more money to be robust against increase of electrical load up to 30 %. On the contrary, this system can save 9.84 % in its energy costs by reducing the electrical demand up to 30 %. Through successful implementation of demand response concept, total operation cost of CHP system in the maximum, mid and minimum robust conditions is $ 3839.944, $ 3490.243 and $ 3149.258, respectively. So, it can be seen that under employment of DRP, CHP system can be robust against 30 % more electrical load in the maximum robust condition by experiencing 0.65 % less increase of payment in comparison with the similar condition without DRP. Also, as shown in Fig. 7, operation cost of CHP system in the mid and minimum robust conditions is reduce up to 0.62 % and 0.54 %, respectively. So, it can be

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concluded that economic stable operation of CHP system can be established under sever uncertainty of electrical load using DRP.

In line with the results expressed above, the total purchased power from upstream network and the total procured gas from gas network in the minimum, mid and maximum robust conditions ignoring/considering DRP are illustrated in Figs 8 and 9, respectively.

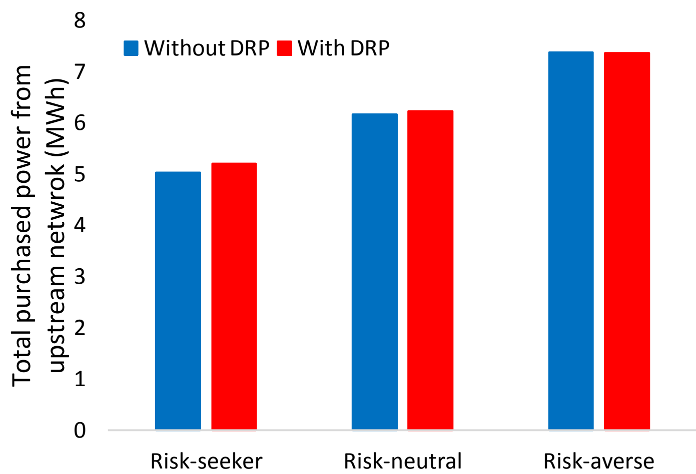

Fig. 8. Total purchased power from upstream network with/without DRP in a typical day in winter

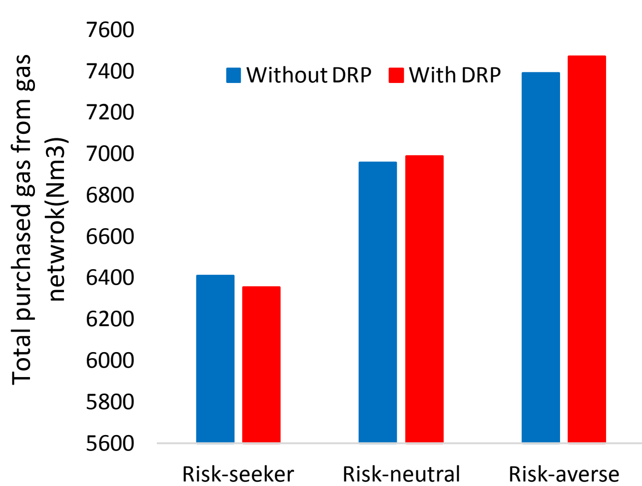

Fig. 9. Total purchased gas from gas network with/without DRP in a typical day in winter

It can be seen from Figs. 8 and 9 that in order to supply the electrical demand in the maximum robust condition in which electrical demand is in its maximum possible value, purchased

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electricity from upstream network and procured gas from gas network are increased. The strategies taken in various possible conditions are different by ignoring/considering DRP. For example, in the minimum robust condition and by considering demand response concept, purchased power from upstream network is increased while procured gas is reduced in comparison with the case where DRP is neglected. This happens when electrical demand is in its minimum possible value. In fact, due to optimal strategies provided by robust optimization in this condition under DRP, CHP system aims to supply thermal demands through converting electrical power into heat. On the other hand, under DRP implementation in the maximum robust condition, gas procurement has been increased while electricity procurement has been decreased in comparison with the case where DRP is ignored.

As a result of increment in gas procurement in the maximum robust condition in comparison with deterministic and minimum robust conditions, generated heat by SH and DHW boilers have been increased. It should be noted that implementation of DRP in each of the mentioned conditions has led to optimal revision of electrical consumption pattern which has consequently changed gas consumption. Therefore the heat generation by SH and DHW boilers has been optimally changed in all maximum, mid and minimum robust conditions. As an illustrative example, generated heat by SH and DHW boilers in maximum, mid and minimum robust conditions with/without DRP is shown in Figs. 10 and 11, respectively.

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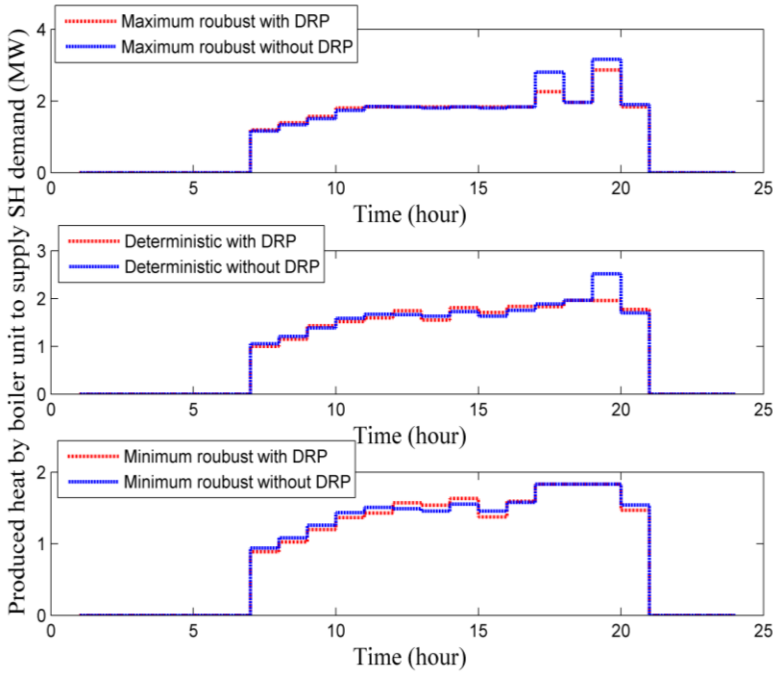

Fig. 10. Generated heat by SH boiler in a typical day in winter

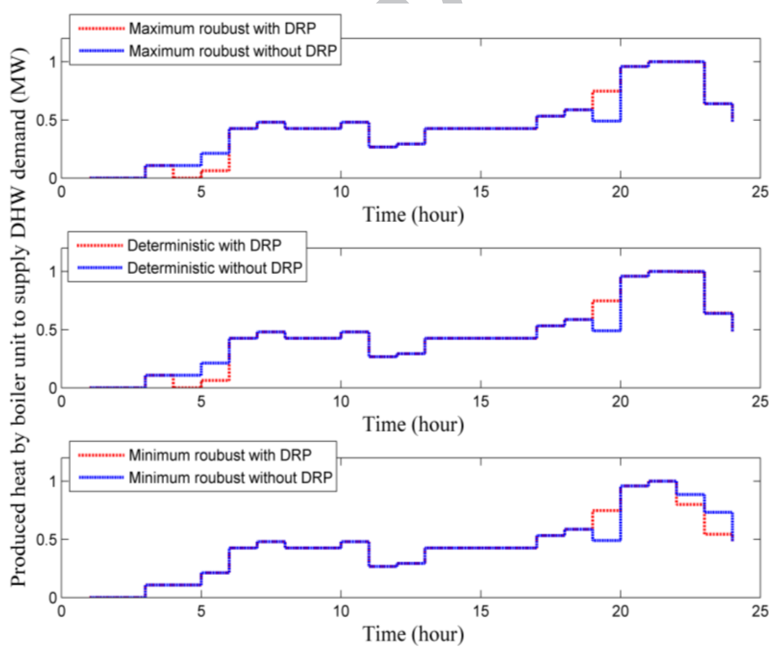

Fig. 11. Generated heat by DHW boiler in a typical day in winter

As a result of increase in electrical demand in the maximum robust condition with/without DRP in comparison with other two cases, generated electric power by gas turbine in the maximum robust condition with/without DRP has been increased which is depicted in Fig. 12.

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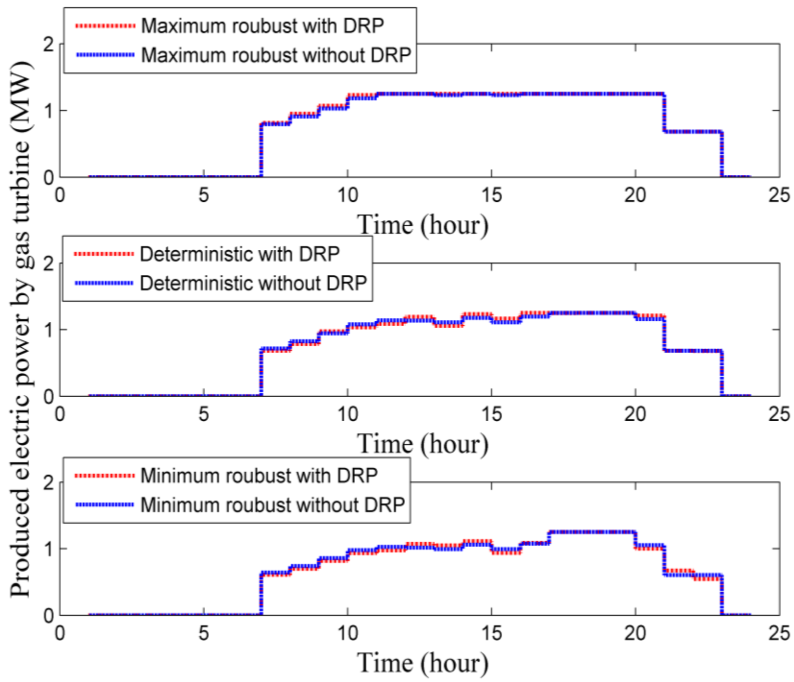

Fig. 12. Generated power by gas turbine in a typical day in winter

According to this figure, in comparison with the mid and minimum robust conditions, CHP system is more responsible to supply energy demand in the maximum robust condition. This is mainly resulted from taken risk-averse strategies in this condition which allow the operator to use the whole potentials to handle uncertainty. However, risk-seeking strategies provided by robust optimization method allow the operator to reduce generation capacity of CHP as much as possible to gain economic benefit in the minimum robust condition.

4.2.2. Summer season

Robust performance of CHP system is studied under uncertainty of electrical load in summer season. Robust operation cost of studied system in a typical day in summer is illustrated without/with DRP in 11 iterations in Fig. 13.

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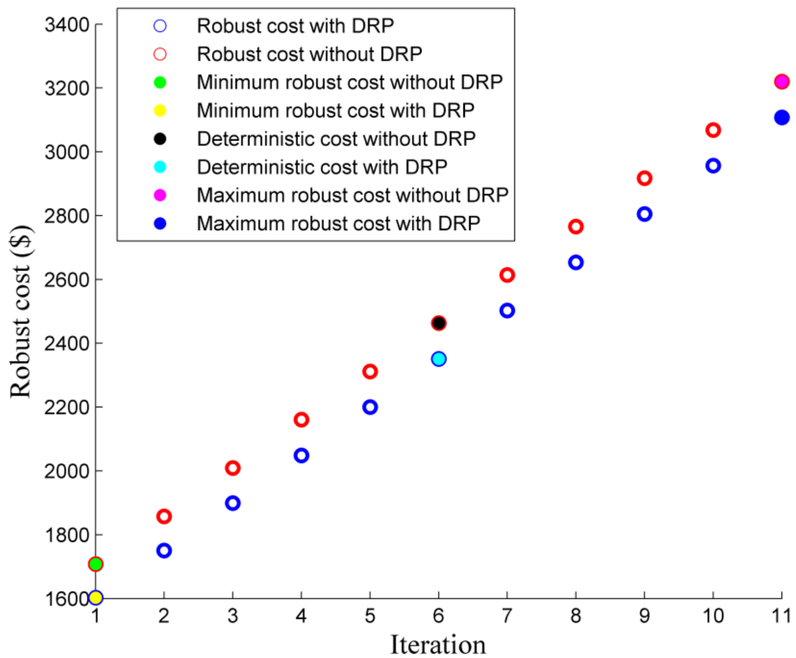

Fig. 13. Robust cost without/with DRP in a typical day in summer

According to this Fig, total operation cost of CHP system without DRP in the maximum, mid and minimum robust conditions is $ 3219.748, $ 2463.020 and $ 1707.829, respectively. By considering DRP, total operation cost of system in the mentioned conditions would be $ 3107.931, $ 2351.203 and $ 1602.401, respectively. Under positive impact of DRP, these cost in the mentioned conditions are reduced 3.47 %, 4.53 % and 6.17 %, respectively. In simple words, operator of CHP system can overcome of 30 % more electrical load under 6.17 % less operation cost through positive implementation of DRP.

Total purchased power from upstream network in different conditions is illustrated in Fig. 14.

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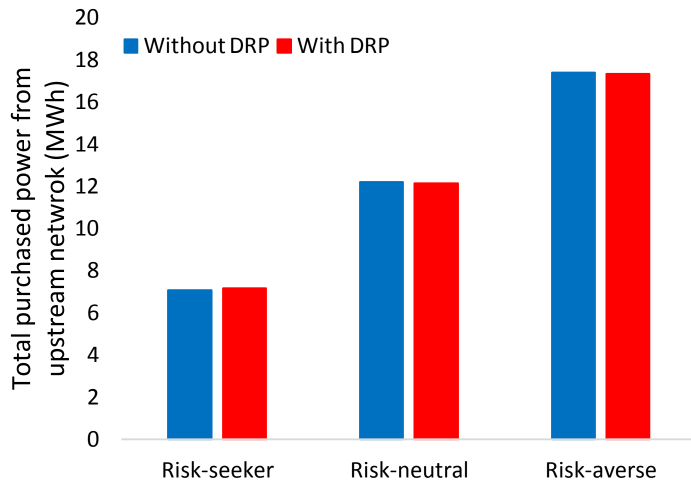

Fig. 14. Total purchased power from upstream network with/without DRP in a typical day in summer

According to this Fig, optimal robust strategies are obtained to be used by the operator. As depicted, total purchased power from upstream network is increased proportional with the increase of electrical load in the maximum robust condition. On the other hand, it can be seen that total imported power is reduced due to reduction of electrical load in the minimum robust condition. It is noteworthy that optimal operation of CHP system is enhanced under implementation of DRP according to which purchased power from upstream network is obtained as shown in Fig. 14.

4.2.3. Transitional seasons

Total robust operation cost of CHP system in different conditions in transitional seasons is illustrated in Fig. 15.

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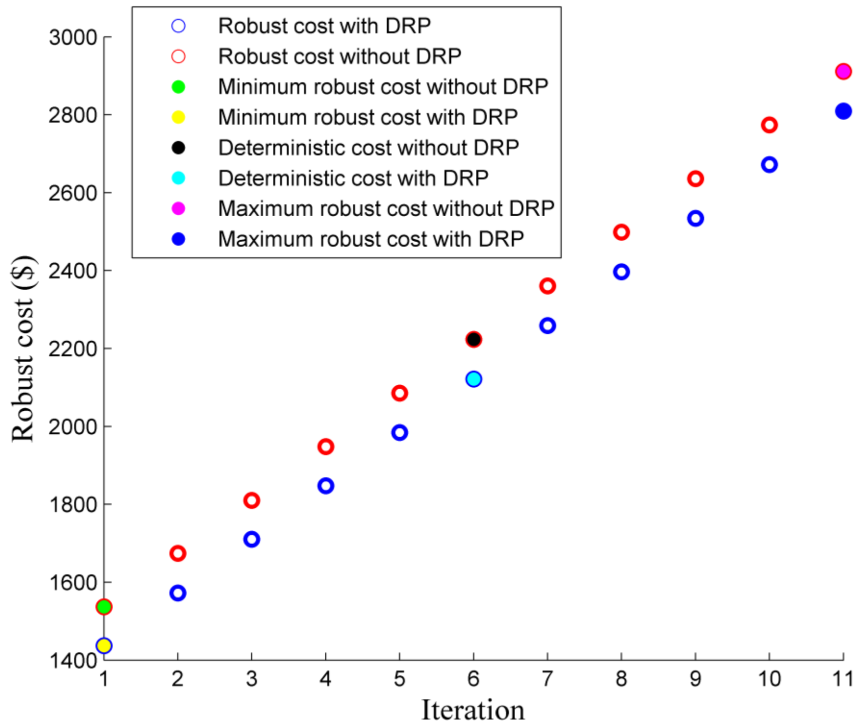

Fig. 16. Robust cost without/with DRP in a typical day in transitional seasons

According to this Fig, total operation cost of CHP system without considering DRP in the maximum, mid and minimum robust conditions is $ 2911.222, $ 2223.288 and $ 1536.715, respectively. Under positive impact of DRP, the mentioned costs are reduced 3.49 %, 4.57 % and 6.48 %, respectively.

Total imported power from upstream network in maximum, mid and minimum robust conditions with/without DRP is illustrated in Fig 17.

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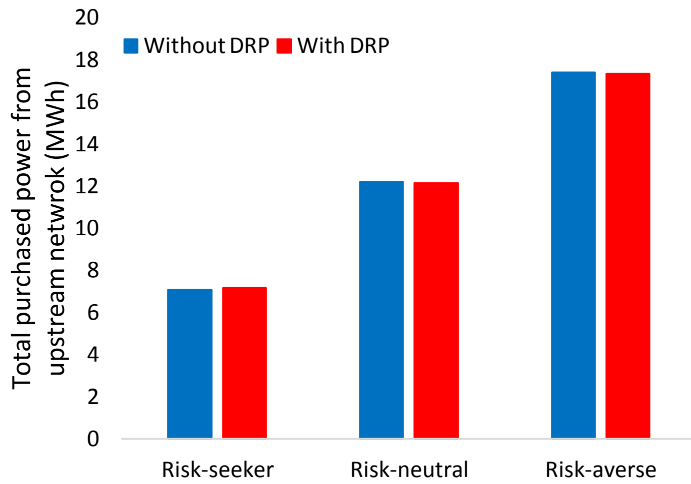

Fig. 17. Total purchased power from upstream network with/without DRP in a typical day in transitional seasons

According to this Fig, total imported power from upstream network is increased to make up the energy deficiency caused by increase of electrical load in the maximum robust condition. On the other hand, due to reduction of electrical demand in the minimum robust condition, total imported power from upstream network is reduced to gain maximum possible economic benefit through reduction of cost of power procurement from upstream network.

For more comparison, simulation results obtained in different seasons are summarized in Tables 4-7.

Table 4: Results obtained in winter

Condition	No DRP			With DRP		
	Minimum robust	Mid robust	Maximum robust	Minimum robust	Mid robust	Maximum robust
Total daily electrical load (MWh)	7.892	11.274	14.656	7.892	11.274	14.656
Total seasonal electrical load (MWh)	710.256	1014.651	1319.046	710.256	1014.651	1319.046
Total daily imported power (MWh)	5.032	6.163	7.375	5.200	6.224	7.362
Total seasonal imported power (MWh)	452.853	554.629	663.740	468.023	560.145	662.592
Total daily cost of total system ($)	3166.440	3512.218	3865.144	3149.258	3490.243	3839.944
Total seasonal cost of total system ($)	284979.6	316099.6	347862.9	283433.1	314121.8	345594.9

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Table 5: Results obtained in summer

Condition	No DRP Minimum robust	No DRP Mid robust	No DRP Maximum robust	With DRP Minimum robust	With DRP Mid robust	With DRP Maximum robust
Total daily electrical load (MWh)	12.401	17.716	23.031	12.401	17.716	23.031
Total seasonal electrical load (MWh)	1153.320	1647.600	2141.880	1153.320	1647.600	2141.880
Total daily imported power (MWh)	7.056	12.208	17.397	7.150	12.149	17.338
Total seasonal imported power (MWh)	1612.471	1098.714	1565.735	664.981	1129.882	1612.471
Total daily cost of total system ($)	1707.829	2463.020	3219.748	1602.401	2351.203	3107.931
Total seasonal cost of total system ($)	153704.6	221671.8	289777.3	149023.2	218661.9	289037.5

Table 6: Results obtained in transitional seasons

Condition	No DRP Minimum robust	No DRP Mid robust	No DRP Maximum robust	With DRP Minimum robust	With DRP Mid robust	With DRP Maximum robust
Total daily electrical load (MWh)	11.274	16.106	20.937	11.274	16.106	20.937
Total seasonal electrical load (MWh)	2051.850	2931.214	3810.578	2051.850	2931.214	3810.578
Total daily imported power (MWh)	6.528	11.286	16.003	6.475	11.233	15.950
Total seasonal imported power (MWh)	1188.070	2054.033	2912.598	1178.363	2044.327	2902.892
Total daily cost of total system ($)	1536.715	2223.288	2911.222	1437.058	2121.636	2809.570
Total seasonal cost of total system ($)	279682	404638.3	529842.4	261544.6	386137.7	511341.8

Table 7: Annual results

Condition	No DRP Minimum robust	No DRP Mid robust	No DRP Maximum robust	With DRP Minimum robust	With DRP Mid robust	With DRP Maximum robust
Total annual electrical load (MWh)	3915.426	5593.465	7271.504	3915.426	5593.465	7271.504
Total annual imported power (MWh)	3253.394	3707.376	5142.073	2311.367	3734.354	5177.955
Total annual cost of total system ($)	718366.2	942409.7	1167482.6	694000.9	918921.4	1145974.2
Annual cost of total	253706.8	457132.5	661196.1	233639	434957	640491.1

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system without CHP ($)						
Annual cost of CHP system	464659.4	485277.2	506286.5	460361.9	483964.4	505483.1

4.2.3. Sensitivity analysis

In this part, simulations are carried out for different conditions and different efficiencies of all equipment incorporated in CHP system and the results are summarized in Table 8.

Table 8: Annual cost of system under different efficiencies

#		Total annual cost of total systems ($)		
		5 % less efficiencies	0 % more efficiencies	5 % more efficiencies
Minimum robust	No DRP	738962.767	718366.2	699068.386
	With DRP	714456.328	694000.9	674788.824
Mid robust	No DRP	963758.249	942409.7	922319.396
	With DRP	940339.382	918921.4	898924.119
Maximum robust	No DRP	1189439.614	1167482.6	1147021.432
	With DRP	1168131.55	1145974.2	1125538.81

It can be seen from these results that by increasing efficiencies of different units in CHP system, economic performance of system is proportionally enhanced. As shown, under higher efficiencies, total annual cost of system is reduced within different uncertainty levels. Similar conclusions are also true for operation of system under DRP.

5. Conclusion

In this paper, a new robust optimization based framework was proposed for economic operation of CHP system under sever uncertainty and in the presence of demand response concept. Robust optimization was used to determine necessary strategies in the maximum, mid and minimum robust conditions including the maximum, expected and minimum value of electrical demand. Results for a typical day in winter demonstrated that, in order to be robust against 30% more electrical demand under DRP, total payments of CHP system will increase 0.65 % less in comparison with the case DRP is ignored. However, in order to handle such amount of increase of load under DRP in a similar case in summer, total increase of cost of CHP system will be 1.46

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% less in comparison with the case DRP is ignored. This reduction due to positive impact of DRP will be 1.48 % in a typical day in transitional seasons. According to these results, demand response has a more sensible impact on robust/economic performance of CHP system in a hot day in summer than a hot day in summer or a cold day in winter. On the other hand, robust methods determined that due to reduction of electrical demand up to 30%, total payments of CHP system in typical days in winter, summer and transitional seasons can be decreased up to 9.84 %, 30.66 % and 30.88 %, respectively. Under positive impact of DRP, the mentioned reduction rates are 9.76 %, 31.84 % and 32.26 %, respectively. These results mean that DRP has positive impact on the obtained benefit from possible reduction of load in summer and transitional seasons. In winter, however, total obtained benefit from load reduction is slightly decreased under DRP. Totally, annual results depicted that DRP has positive impact on the risk-averse, risk-neutral and risk-seeking performances of CHP system in the maximum and mid and minimum robust conditions.

Furthermore, optimal uncertainty based operation of CHP system is studied subject to different values of efficiencies of energy units and the results demonstrated successful performance of robust optimization method in providing appropriate operating strategies. It is noteworthy that the above-mentioned discussions are also studied under employment of DRP and the results in all daily, seasonal and annual studies under different levels of uncertainty and efficiencies depicted positive impact of such programs in enhancement of economic performance of operating system.

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Highlights

- ✓ Economic operation of CHP system under demand response concept.
- ✓ Uncertainty-based performance CHP system against electrical load uncertainty.
- ✓ Uncertainty modeling via robust optimization technique.
- ✓ Strengthened robust performance of CHP system under demand response concept.

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