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PROFIT-BASED ONLINE OPTIMAL PLANNING OF LOW EMISSION MULTI-ENERGY DISTRIBUTION SYSTEM

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Abstract

This paper proposes a two-stage energy management approach to optimize the operation of the combined electric power, natural gas, heat, and cool in an integrated system (CPGHCS) in the deregulated market. Fixed end receding horizon technique (FERHT) is employed to tackle the uncertainties that evolve from the renewable generation and load demands. In the first stage (day-ahead), the optimal scheduling finds out the electric, gas, heat, and cool output of the energy sources. In the second stage(real-time), the RHT updates the output scheduling of the energy sources by considering the day ahead results and feedback from online measurements. The emission of greenhouse gas cost and a set of realistic constraints are considered in the multi-objective framework. Storage devices are used to mitigate the uncertainties in renewable generation and load and balance the demand and generation, where the operating cost of these storage devices are considered in the proposed approach. To verify the applicability of the proposed approach, it is tested on the modified distribution system. The results reveal that the proposed approach can tackle the uncertainties efficiently and supplies clean energy.

Keywords: Combined cool, Emission cost, Heat, and power, Microgrids, Optimization programs, Power to gas technology.

1. Introduction

The depletion of fossil fuel, environmental pollution, increasing energy demand are the main issues that lead to draw more attention to develop low emission multi-energy systems. This integrated system supplies electric power, natural gas, heat, and cool demands simultaneously. This system includes different types of energy generators, combined heat and power (CHP) units and energy storage devices with the integration of renewable energy resources. These sources work with coupling and interacting between them to achieve low emission and efficient energy systems. The optimal dispatch of the CPGHCS can considerably increase the overall profit in the deregulated market. Many optimization approaches have been proposed to maximize the profit of connected and isolated microgrid (MG) in the competitive market. Table 1 summarizes the literature review of the previous works.

Table 1. Summarize the literature review.

Ref. No.	Year	Methodology
[1]	2008	In this paper, a MG profit was maximized, where the proposed approach considered the MG which suppled electric load solely. However, many cost functions and important constraints are ignored. Besides, the heat, cool, and gas loads with their generation devices and constraints are overridden in the proposed model.
[2]	2014	This paper presented an optimization approach to maximize a MG profit and minimize cost. Where, the proposed approach ignored many important cost functions and constraints which they affect the fidelity of the proposed model. Further, the MG supplied only electric load.
[3]	2015	Authors proposed and energy management system to maximize a MG profit. However, the emission of greenhouse gases costs and its relevant constraints are not considered in the proposed approach. In addition, the proposed model considered the MG supplied only electric load, where thermal, cool and gas loads are not taken into account in the model.
[4]	2016	The demand side and generation side are managed to maximize the MG profit. The proposed model overlooked important cost functions and constraints. Besides, The MG that is considered in the proposed approach supplied only electric load.
[5]	2016	The security constrained is taken into consideration in this model to maximize MG supplying electric load. However, the proposed model ignored the heat, cool, and gas loads and their generation devices and constraints models.
[6]	2012	A two-stage multi-agent real-time optimal operation of a MG is suggested to maximize the profit. However, the emission cost of greenhouse gases and the production cost of the renewable energy sources with many other cost functions and constraints were ignored. The proposed system provided electricity to electric load solely as aforementioned works.
[7]	2016	A new optimization approach was presented for the CHP network to maximize the profit, where the proposed model included a comprehensive model of the CHP. However, the emission cost and many cost functions and constraints were ignored in the proposed approach. Besides, unit commitment strategy was not taken into

		account in the model. Furthermore, the proposed system provides heat and electric demands solely.
[8 ,9]	2009, 2014	An energy management system is proposed for MG to maximize profit. The proposed system includes renewable energy, electrolyze, H_2 storage tank, reformer, boiler, electrical and thermal demands. However, these references ignored the emission cost of greenhouse gases and its constraints. Besides, the authors overlooked the model of carbon capture-based power to gas technology (P2G) and cool generators and their constraints. Furthermore, the presented approach supplied heat and electric loads solely.
[10]	2017	Optimization algorithms were developed to solve the optimization problem of the CHP grid, where the aim was to maximize the profit and reduce environmental cost. However, the electric and heat storage devices were not considered in the proposed approach. In addition, the models of cool and gas generators and their constraints are overridden in the proposed model. Moreover, the model was for a day ahead and could not tackle the uncertainties.
[11]	2015	A stochastic programming framework was developed to find the optimal scheduling of energy resources of the CHP-based MG to maximize the profit. However, the proposed model ignored emission cost and cost of degradation of storage devices. Besides, many important constraints were overlooked as well. Furthermore, the cool and gas loads and generators were not included in the proposed approach.
[12]	2018	An optimization algorithm was developed to minimise the total cost of integrated system under uncertainties that arise from the renewable generation and energy demands. However, the unit commitment strategy and many important constraints were not considered in the proposed approach and the cool system was not taken into account in the model.
[13]	2020	An optimization approach was proposed to minimize the cost for MG supplies electric load solely. However, the heat, cool, and gas systems models were not considered in the proposed optimization problems. Besides, many cost functions and constraints were ignored in the proposed model and the model could not tackle the uncertainties.
[14]	2021	Authors presented an energy management for CHP distribution grid to minimize the cost of the system supplies electric and heat loads. However, model of cost function and constraints relevant to the cool and gas systems were not included in the proposed system.

In this paper, an online two-stage energy management system to optimize the operation of the CPGHCS under deregulated market is proposed. The emission cost of greenhouse gases and a set of realistic constraints are considered in this model. The aim is to maximize the profit of the system and find out the optimal scheduling of different types of energy sources. According to the literature, there is no study proposes a model of optimization approach under the competitive market of an integrated system. Where, this system includes electric, gas, heat, and cool systems and a model of each system separately with a comprehensive model of interaction between these systems.

In addition, the proposed system has renewable energy resources and power to gas (P2G) technology to capture the CO_2 and achieve low emission energy system.

The environmental cost is considered as well in the proposed deregulated market, which makes the objective function as multi-objective optimization. Further, unit commitment (UC) is taken into account in the proposed model with a set of constraints which relevant to each system and the interface between the systems. Furthermore, the FERHT is employed to tackle the uncertainties that arise from the renewable generation and different energy demands.

2. Structure of the CPGHCS and Modeling

The proposed structure of the CPGHCS is shown in Fig. 1. The CPGHCS can apply to a small community, hospital, military site, university campus. The CPGHCS consists of a power MG, micro-gas system, micro-heat system, and micro-cool system. The interface between these systems in the CPGHCS is achieved through MT, FC, gas boiler (GB), electric heater (EH), electric chiller (EC), absorption chiller (AC), and P2G technology. The CHP-based MT is driven by natural gas to generate simultaneously power and heat, while the FC transforms the natural gas to power, while GB converts the natural gas to heat and EH utilizes the electricity to generates heat. Besides, EC transforms the electricity to cool, whereas AC converts the heat to cool. In the P2G system, the CO_2 is captured from CHP, where CO_2 with H_2 produce synthetic natural gas (SNG), the electricity is provided from the MG. This process reduces the damage of the environment by reducing the CO_2 emission to the atmosphere. The demand factors of different loads are satisfied by exchanging energy between different systems and trading energy with utility grid to supply peak demands.

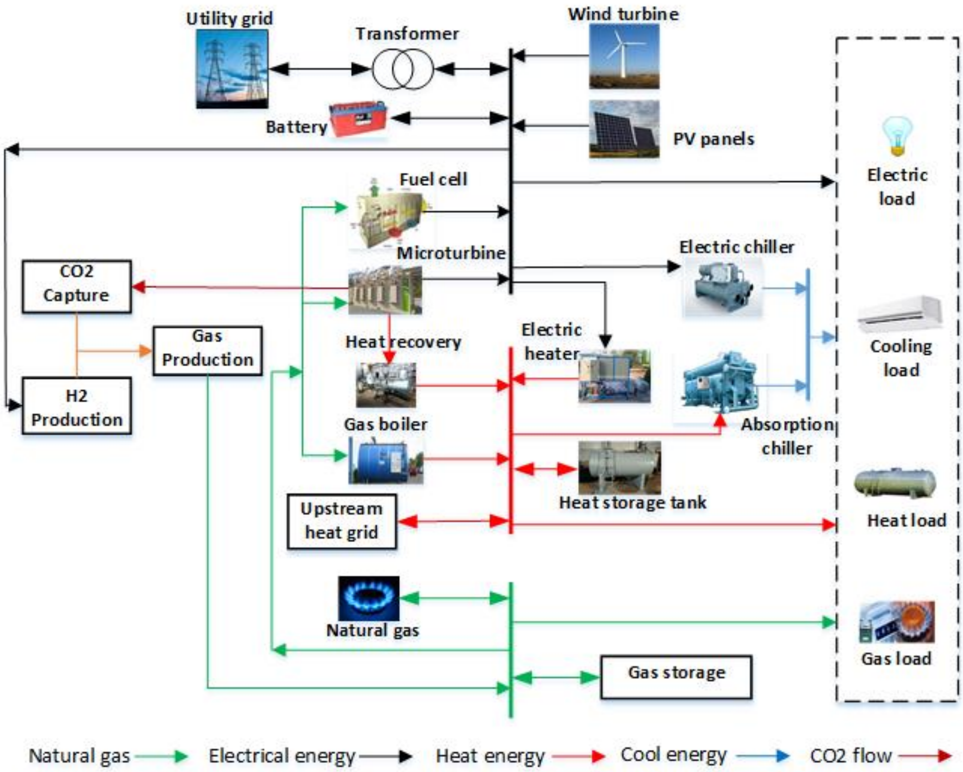


Fig. 1. Schematic of the proposed CPGHCS.

2.1. Micro turbine model

In this paper, the CHP-based MT unit supplies power and heat simultaneously. The MT is driven by NG, where the consumption of gas is determined as follows [12]:

$$gc_{MT}(t) = U_{MT}(t).P_{MT}(t)/(L_{NG,MT}.\eta_{MT}) \tag{1}$$

where $P_{MT}(t)$ is the output electrical power of the MT (kWh), $L_{NG,MT}$ is the low heating value (LHV) of the natural gas (kWh/m^3), η_{MT} is the efficiency of MT, $U_{MT}(t)$ is the on/off state of the MT.

The relation between the produced electrical and heat power is formulated as follows:

$$H_{MT}(t) = U_{MT}.P_{MT}(t).[1 - \delta_{MT} - \delta_1].\delta_{hr}/\eta_{MT} \tag{2}$$

where δ_1 is the heat loss factor of the MT and δ_{hr} is the efficiency of heat recovery. The cost of NG consumption by MT-based CHP is calculated by the following equation:

$$C_{MT}(t) = gc_{MT}(t).p_g \tag{3}$$

where p_g is the price of natural gas($/m^3).

2.2. Fuel cell model

The fuel consumption by the FC is calculated by employing the following equation [12]:

$$gc_{FC}(t) = U_{FC}(t).P_{FC}(t)/(L_{NG,FC}.\eta_{FC}) \tag{4}$$

where $P_{FC}(t)$ is the output power of the FC (kWh), η_{FC} is the efficiency of the FC, and $U_{FC}(t)$ is the on/off state. The cost of fuel consumption of the FC is formulated as follows:

$$C_{FC}(t) = gc_{FC}(t).p_g \tag{5}$$

2.3. Storage battery

The battery (BAT) operation is described and formulated as follows [15]:

$$W_b(t) = W_b(t-1) - \Delta t.\left(\frac{P_{bdis}(t)}{\eta_{dis}}\right) + \Delta t.P_{bch}(t).\eta_{ch} \tag{6}$$

where $W_b(t)$, $W_b(t-1)$ are the state of charge of the BAT at the current and previous time respectively. $P_{bch}(t)$ and $P_{bdis}(t)$ are the BAT charging and discharging power respectively. η_{ch} and η_{dis} are the efficiencies. Δt is the sampling time.

2.4. Interacting power with the utility grid

The cost of trading power with the utility grid is formulated as follows:

$$C_{U,P}(t) = P_U(t).p_{U,P}(t) \tag{7}$$

where $p_{U,P}(t)$ is the trading power with the upstream grid, (+) for purchasing power (-) for selling power. $p_{\boldsymbol{U}}(t)$ is the exchanging power price($/kWh).

2.5. On/off cost of FC and MT

These costs are determined by the following equations [16]:

$$SU(t) = S_c \,.\, (\delta(t) - \delta(t).\delta(t-1)) \tag{8}$$

$$SD(t) = S_d \,.\, (\delta(t-1) - \delta(t).\delta(t-1)) \tag{9}$$

where S_c and S_d are the price of the start-up and shutdown cost of the FC and MT.

2.6. Environmental damage cost

The emission of CO_2, SO_2, NOx, and PM which are caused by burning the fossil fuel leads to damage to the environment. This damage is converted to the monetary concept by using the following equations:

Environment cost of MT

$$C_{E,MT}(t) = \sum_{j=1}^{M} E_{j,MT} \,.\, C_j . P_{MT}(t) \tag{10}$$

Environment cost of FC

$$C_{E,FC}(t) = \sum_{j=1}^{M} E_{j,FC} \,.\, C_j . P_{FC}(t) \tag{11}$$

where $E_{j,MT}$ and $E_{j,FC}$ (kg/kWh) are the emission amount of j^{th} GHG from the MT, FC respectively, C_j ($/kg) is an expense of emission of j^{th} GHG.

2.7. Gas boiler model

The GB is driven by NG, where gas consumption is calculated as follows:

$$gc_{gb}(t) = H_{gb} / (L_{NG,gb} . \eta_{gb}) \tag{12}$$

where $H_{gb}(t)$ is the heat generated by the GB and η_{gb} is the efficiency of GB. The cost of NG consumption by GB is formulated as follows [17]:

$$C_{gb}(t) = gc_{gb}(t) . p_g \tag{13}$$

2.8. Electric heater model

The EH supplies heat to the thermal loads, where the output heat is expressed as:

$$H_{eh}(t) = P_{eh}(t) . \eta_{eh} \tag{14}$$

where $P_{\boldsymbol{eh}}(t)$ is the consumed electric power, η_{eh} is the efficiency of EH.

2.9. Heat storage model

The following equation describes the operating of HS [18]

$$W_{hs}(t) = W_{hs}(t-1).(1-\rho_{hs}) - \Delta t . \left(\frac{H_{hs,dis}}{\eta_{hs,dis}}\right) + \Delta t . H_{hs,ch} \,.\, \eta_{hs,ch} \tag{15}$$

where $W_{hs}(t)$ and $W_{hs}(t-1)$ heat storage state at the current and previous interval. $H_{hs,dis}(t)$ and $H_{hs,ch}(t)$ heat power released and stored of HS (kW). $\boldsymbol{\rho_{hs}}$ is the heat loss rate.

2.10. Interacting heat with the upstream grid

The cost of exchanging heat with the upstream grid is formulated as follows:

$$C_{U,H}(t) = H_U(t).\, p_{U,H}(t) \tag{16}$$

where $H_U(t)$ is the trading heat with the utility grid, (+) for purchasing power (-) for selling power. The $p_{U,H}(t)$ is the exchanging heat price($/kWh).

2.11. Electric chiller model

The electric chiller provides the cooling load by cooling power. The output cooling power of the EC is formulated as follows:

$$C_{ec}(t) = P_{ec}(t).\, COP_{ec} \tag{17}$$

where $P_{ec}(t)$ is the electric power which is supplied to EC and COP_{ech} is the coefficient of performance.

2.12. Absorption chiller model

The absorption chiller provides the cooling load by cooling power. The output cooling power of AC is determined by the following equation:

$$C_{ac}(t) = H_{ac}(t).\, COP_{ac} \tag{18}$$

where $H_{ac}(t)$ is heat which is supplied to AC and COP_{ac} is the coefficient of performance.

2.13. P2G system

The P2G system consists of three subsystems: H_2 generation system, CO_2 capture system, and SNG production system. The description of each subsystem is as follows:

a. H_2 generation system

In this system, the H_2 is produced by electrolyzing the water, where the electric power is supplied from the MG. The following equation is used to represent the H_2 production [12].

$$P_{H_2}(t) = P_{eH_2}(t).\, \eta_{H_2}/L_{H_2} \tag{19}$$

where $P_{eH_2}(t)$ is the electrical power (kWh) consumed at time t for producing H_2, η_{H_2} is the efficiency of H_2 production, and L_{H_2} the low heating value of H_2 (kWh/m^3).

b. CO_2 capture system

The CO_2 capture technology captures the CO_2 that is emitted by CHP-based MT by adsorptive capture process, details in [19].

c. SNG production system

CO_2 and H_2 are used to generate SNG. The process of SNG production is described as $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$. Practically, the losses of the P2G process reduces the ratio of CO_2 to CH_4 volume to less than 1. Therefore, the following equation is employed for the P2G [12, 20].

$$P_{SNG}(t) = \eta_{SNG}.\, P_{CO_2}(t) \tag{20}$$

where $P_{SNG}(t)$ is the production of SNG (m^3/h), η_{SNG} is the efficiency of SNG production, $P_{CO_2}(t)$ is CO_2 (m^3/h) consumption for SNG production.

2.14. Gas storage model

The following equation describes the operating of GS [15].

$$W_{gs}(t) = W_{gs}(t-1) - \Delta t.\left(\frac{G_{gs,dis}}{\eta_{gs,dis}}\right) + \Delta t. G_{gs,ch} . \eta_{gs,ch} \quad (21)$$

where $W_{gs}(t)$ and $W_{gs}(t-1)$ gas storage state at the current and previous interval. $G_{gs,dis}(t)$ and $G_{gs,ch}(t)$ gas released and stored of GS (kW).

3. Optimization Problem

The aim of this work is to maximize the profit of the system, where the profit depends not only on the revenue but also on the expenses. The revenue of the MG is obtained from selling power, heat, gas, and cool to the consumers and the utility grid. It is assumed that the MG sells power to the consumers and the utility by open market price (OMP). The proposed profit objective functions for the day ahead and real-time are formulated as follows:

$$\max(F) \quad (22)$$

$$F = revenue - expense \quad (23)$$

The profit of the system is formulated as follows:

$$F = revenue - expense \quad (23)$$

$$F = \sum_{t=0}^{T-1-k} \{P_{FC}(t+k). p_{U,P}(t+k). U_{FC}(t+k) + P_{MT}(t+k). p_{U,P}(t+k). U_{MT}(t+k)$$
$$+P_{b,dis}(t+k) p_{U,P}(t+k) + P_W(t+k). p_{U,P}(t+k) + P_{PV}(t+k). p_{U,P}(t+k)$$
$$+H_{gb}(t+k). p_{U,H}(t+k) + H_{eh}(t+k). p_{U,H}(t+k) + H_{gb}(t+k). p_{U,H}(t+k)$$
$$+H_{hs,dis}(t+k). p_{U,H}(t+k) + H_{MT}(t+k). p_{U,H}(t+k). U_{MT}(t+k)$$
$$+C_{ec}(t+k). p_c + C_{ac}(t+k). p_c + G_{gs,dis}(t+k). p_{U,G} + G_{P2G}(t+k). p_{U,G}$$
$$-(C_b(t+k) + SU_{MT}(t+k) + SU_{FC}(t+k) + SD_{MT}(t+k) + SD_{FC}(t+k)$$
$$+C_{PW}(t+k) + C_{PV}(t+k) + C_{om,MT}(t+k) + C_{om,FC}(t+k) + C_{om,gb}(t+k)$$
$$+C_{om,eh}(t+k) + C_{om,ec}(t+k) + C_{om,ac}(t+k) + C_{om,hs}(t+k)$$
$$+C_{om,gs}(t+k) + C_{E,MT}(t+k) + C_{E,FC}(t+k) + p_{CO_2}. P_{SNG}(t+k)$$
$$-C_{CO2}. P_{CO_2}(t+k). \rho_{CO2})\} \quad (24)$$

where k is the current state.

4. Modeling of Constraints

The following proposed constraints should be met when solving the optimization problem.

• Energy balance constraints

The electrical, heat, gas and cool demands should be satisfied at each time step.

a. Electrical power constraint

$$\sum_{t=0}^{T-1-k} \{P_{MT}(t+k) + P_{FC}(t+k) + P_w(t+k) + P_{PV}(t+k) + P_{b,dis}(t+k) + P_{U,p}(t+k) = P_L(t+k) + P_{b,ch}(t+k) + P_{U,s}(t+k) + P_{eh}(t+k) + P_{ec}(t+k) + P_{eH_2}(t+k)\} \quad (25)$$

where $P_w(t+k)$ and $P_{PV}(t+k)$ are the wind turbine and PV panels power, $P_{\boldsymbol{U,p}}(t+k)$ and $P_{\boldsymbol{U,s}}(t+k)$ are purchasing and selling power from/to the utility grid, and $P_L(t+k)$ is the electrical load.

b. Heat power constraint

This constraint is formulated as follows:

$$\sum_{t=0}^{T-1-k}\{H_{MT}(t+k)+H_{gb}(t+k)+H_{eh}(t+k)+H_{hs,dis}(t+k)+H_{U,p}(t+k)=H_L(t+k)+H_{hs,ch}(t+k)+H_{U,s}(t+k)+H_{ac}(t+k)\} \quad (26)$$

where $H_{\boldsymbol{U,p}}(t+k)$ and $H_{\boldsymbol{U,s}}(t+k)$ are purchasing and selling heat from/to the utility grid, and $H_L(t+k)$ is the heat load.

c. Cool power constraint

This constraint is as follows:

$$\sum_{t=0}^{T-1-k} C_{ec}(t+k)+C_{ac}(t+k)=C_L(k+t) \quad (27)$$

where $C_L(t+k)$ is the cool load.

d. Gas power constraint

This constraint is as follows:

$$\sum_{t=0}^{T-1-k}\{G_{gs,dis}(t+k)+G_{U,p}(t+k)+G_{P2G}(t+k)=G_L(t+k)+G_{hs,ch}(t+k)+G_{U,s}(t+k)+gc_{FC}(t+k)+gc_{MT}(t+k)+gc_{gb}(t+k)\} \quad (28)$$

where $G_L(t+k)$ is the gas load.

• Generators operating constraints

The following constraints for generators should be satisfied

a. Capacity constraints

$$P_{min} \le P(t+k) \le P_{max} \quad (29)$$

where $P(t+k)$ is the output power of MT and FC.

b. Ramp rate constraint

$$-DR.\Delta t \le P(t+1+k)-P(t+k) \le UR \quad (30)$$

where DR and UR are ramping up and down of the generators.

• Storage battery constraints

These constraints as follows:

a. State of charge constraint [14]

$$W_{b,min} \le W_b(t+k) \le W_{b,max} \quad (31)$$

b. Charging and discharging power [14]

$$\delta_{bch}(t+k).P_{bchmin} \leq P_{bch}(t+k) \leq \delta_{bch}(t+k).P_{bchmax} \quad (32)$$

$$\delta_{bdis}(t+k).P_{bdismin} \leq P_{bdis}(t+k) \leq \delta_{bdis}(t+k).P_{bdismax} \quad (33)$$

$$\delta_{bch}(\mathrm{t}+\mathrm{k}) + \delta_{bdis}(t+k) \leq 1 \quad (34)$$

where $\delta_{bch}(\mathrm{t}+\mathrm{k})$ and $\delta_{bdis}(\mathrm{t}+\mathrm{k})$ are binary variables that are employed to determine the storage battery operations status.

- **Exchanging power with the utility grid constraints**

$$\delta_{U,p}(t).P_{U,pmin} \leq P_{U,p}(t) \leq \delta_{U,p}(t).P_{U,pmax} \quad (35)$$

$$\delta_{U,s}(t).P_{U,smin} \leq P_{U,s}(t) \leq \delta_{U,s}(t).P_{U,smax} \quad (36)$$

$$\delta_{gp}(t) + \delta_{gs}(t) \leq 1 \quad (37)$$

- **Heat storage constraints**

These constraints are as follows:

a. State of charge constraint

$$W_{hs,min} \leq W_{hs}(t+k) \leq W_{hs,max} \quad (38)$$

b. Charging and discharging power

$$\delta_{hs,ch}(t+k).H_{hs,ch-min} \leq H_{hs,ch}(t+k) \leq \delta_{hs,ch}(t+k).H_{hs,ch-max} \quad (39)$$

$$\delta_{hs,dis}(t+k).H_{hs,dis-min} \leq H_{hs,dis}(t+k) \leq \delta_{bdis}(t).H_{hs,dis-max} \quad (40)$$

$$\delta_{hs,ch}(\mathrm{t}+\mathrm{k}) + \delta_{hs,dis}(t+k) \leq 1 \quad (41)$$

- **Boiler constraint**

$$\boldsymbol{H_{gb,min} \leq H_{gb}(t+k) \leq H_{gb,max}} \quad (42)$$

- **Electric heater constraint**

$$H_{eh,min} \leq H_{eh}(t+k) \leq H_{eh,max} \quad (43)$$

- **Exchanging heat power with the utility grid constraints**

$$\delta_{U,p}(t).H_{U,pmin} \leq H_{U,p}(t) \leq H_{U,p}(t).H_{U,pmax} \quad (44)$$

$$\delta_{U,s}(t).H_{U,smin} \leq H_{U,s}(t) \leq \delta_{U,s}(t).H_{U,smax} \quad (45)$$

$$\delta_{gp}(t) + \delta_{gs}(t) \leq 1 \quad (46)$$

- **Electric chiller constraints**

$$C_{ec,min} \leq C_{ec}(t+k) \leq C_{ec,max} \quad (47)$$

- **Absorption chiller constraints**

$$C_{ac,min} \leq C_{ah}(t+k) \leq C_{ac,max} \quad (48)$$

- **Gas storage Constraints**

These constraints are calculated by using the following equations

a. State of charge constraint

$$W_{gs,min} \leq W_{gs}(t+k) \leq W_{gs,max} \tag{49}$$

b. Charging and discharging power

$$\delta_{gs,ch}(t+k).G_{gs,ch-min} \leq G_{gs,ch}(t+k) \leq \delta_{gs,ch}(t+k).G_{gs,ch-max} \tag{50}$$

$$\delta_{gs,dis}(t+k).G_{gs,dis-min} \leq G_{gs,dis}(t+k) \leq \delta_{gdis}(t).G_{gs,dis-max} \tag{51}$$

$$\delta_{gs,ch}(t+k) + \delta_{gs,dis}\,(t+k) \leq 1 \tag{52}$$

where $\delta_{gs,ch}(\mathrm{t}+\mathrm{k})$ and $\delta_{gs,dis}(\mathrm{t}+\mathrm{k})$ are binary variables that are employed to determine the heat storage operations

- **Exchanging gas with the utility grid constraints**

$$\delta_{U,p}(t)\,.G_{U,pmin} \leq G_{U,p}(t) \leq G_{U,p}(t).H_{U,pmax} \tag{53}$$

$$\delta_{U,s}(t)\,.G_{U,smin} \leq G_{U,s}(t) \leq \delta_{U,s}(t).G_{U,smax} \tag{54}$$

$$\delta_{gp}(t) + \delta_{gs}(t) \leq 1 \tag{55}$$

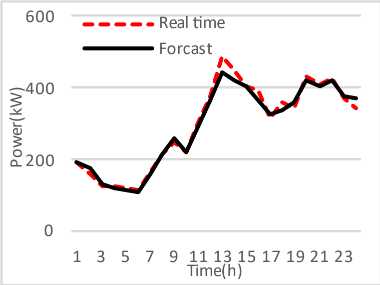
5.Experiential Setup

To verify the robustness and effectiveness of the CPGHCS and to validate the mathematical model, the proposed model is applied to the low voltage the CPGHCS, which is shown in Fig. 1. The system and components parameters are taken from invaluable paper and from real scenario to make the fidelity of the proposed model reliable. The electrical, thermal, cool, gas load demands, WT and PV units, and electrical and thermal prices [7, 12, 21] are shown in Fig. 2. The red dotted line represents the real-time data while the black one represents the forecasted values.

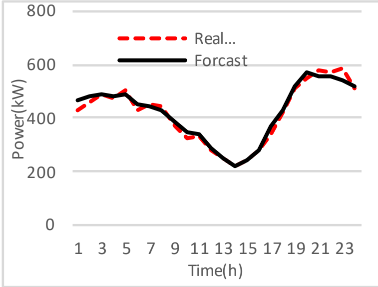
The rated charging and discharging power are 90 kWh. The rated and minimum energy of BAT are 300 kWh and 90 kWh, respectively. The rated and minimum stored energy of heat storage are 300 kWh and 90 kWh, respectively. While, the rated and minimum stored energy of gas storage are 100 kWh and 20 kWh, respectively. The rated gas boiler and the electric heater is 100 kWh and 500 kWh respectively. The ramp rate of CHP and FC is set at 100 kW and 20 kW. The maximum and minimum output power of the CHP, FC, GB, EH, EC, AC, and exchanging power, heat, and gas with the utility grid are listed in Table 2.

Table. 2 Relevant parameters.

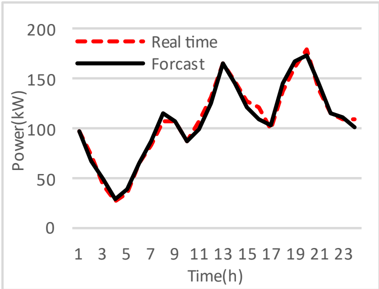
Type	Minimum power (kW)	Maximum power (kW)
CHP	20	200
FC	10	40
GB	0	100
EH	0	500
ECH	0	200
ACH	0	200
P_U	10	300
$P_{U,H}$	10	200
$P_{U,G}$	50	700



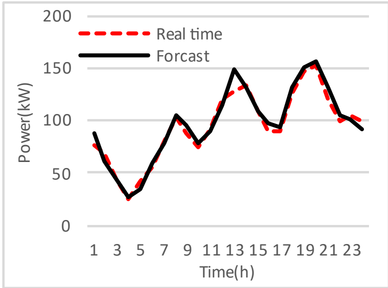
(a) Electrical load



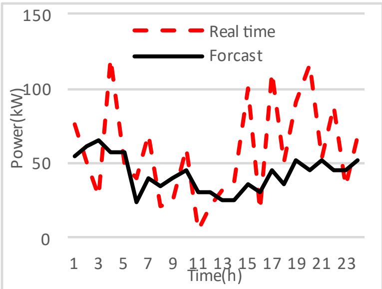
(b) Thermal load



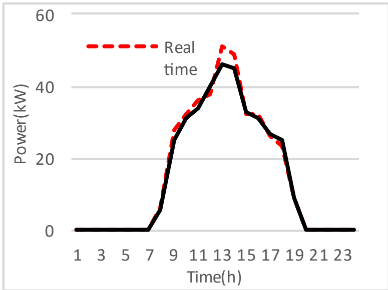
(c) Cool load



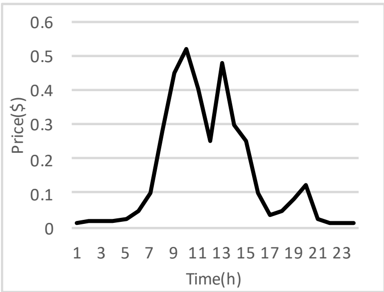
(d) Gas load



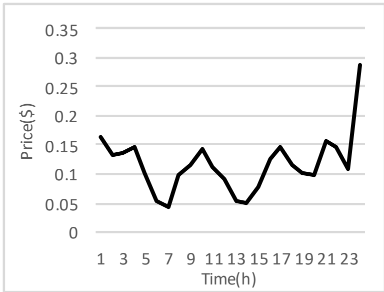
(e) Power of WT



(f) Power of PV unit



(g) Electric market price



(h) Thermal market price

Fig. 2. Hourly profile of, electric load, thermal load, cool load, gas load, power of WT, power of PV unit, electric market price, and thermal market price.

6. Solution of the Optimization Problem

The proposed optimization approach is formulated by using mixed integer nonlinear program. ILOG's CPLEX software solver is used to solve this optimization problem, where the Microsoft Excel is interfaced with the CPLEX to show the results [22]. The CPLEX is based on branch and bound algorithm. Where the main merit of this algorithm is when the solution is obtained, this means the solution is globally optimum [23]. The CPLEX is used to solve the problem because Matlab has deficiency to solve the mixed integer nonlinear program optimization problem. The flowchart which is depicted in Fig. 3 shows the data process and solution of the optimization problem.

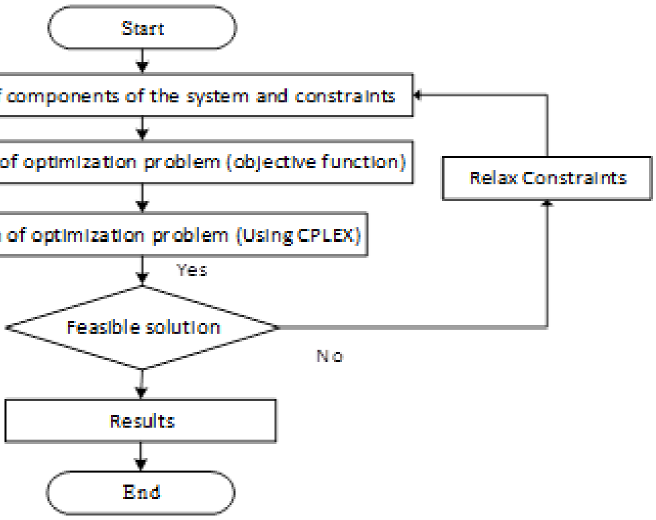


Fig. 3. Flowchart of data process.

7. Results and Discussion

Figure 4 shows the optimal schedule of the electric system for both day-ahead and real-time. While Fig. 5 depicts the optimal schedule of heat system for day-ahead and real-time. It can be observed from these figures that the CHP-based MT is committed over the entire scheduling day to supply the electric and thermal loads, where the CHP-based MT output is constrained by thermal loads. The FC is operated over the whole scheduling horizon. Both the CHP and FC supply less power at hours 1- 3 because the open market price has the lowest values at these hours. However, the CHP provides maximum power at hour 3 in the case of real-time because at real-time the wind generation is quite lower than in the forecasted case.

Besides, the BAT is discharged when the open market price has high values to increase the revenue of the system because the system sells the electricity to the consumers with the open market price. In the case of the day ahead, the BAT discharges at hour 4 to compensate the deficiency in the wind generation. Further, the BAT is charged with the highest possible power at hour 16 in case of the day ahead, while the battery is charged less power in case of real-time because the load is much higher. Furthermore, the CPGHCS system buys electric power from the utility grid over the whole scheduling day to supply the electric, heat, cool loads.

The optimal schedule of the heating system is shown in Fig. 5. It can be seen that the GB is operated with the maximum possible output for both cases over the entire scheduling horizon because the GB has a low operating cost. Besides, the CHP-based MT supplies heat over the whole scheduling day because the CHP-based MT is an economical way to supply heat, where the surplus heat sells to the utility grid to increase the revenue of the system. In addition, the heat storage is charged and discharged according to the values of the heat load and the price of exchanging heat with the upstream grid to increase the revenue of the system.

Further, the system sells the highest possible heat to the utility grid when the price has the highest values and the renewable generation abundant at hours 1-3 and 10 to increase the profit of the system. Moreover, the system sells the lowest heat to the utility grid at hour 14 because the heating price has low value, and the electrical price has the highest value. Therefore, the heat output of the EH is quite low to reduce the expense of the system. In the case of real-time, the system does not sell heat to the utility grid because the electric load is higher than the day ahead case. Therefore, the EH heater supplies less heat compared to the day ahead case.

Figure 6 shows the optimal schedule of the gas system. It can be noticed that the P2G system uses electricity to produce natural gas over the entire scheduling horizon by capturing the CO_2 which is emitted from the CHP. This leads to reduce the environmental cost and increase the profit. The highest gas consumption occurs at hour 20 when the electric and heat load has high value. The lowest gas consumption is at hours 4 and 5 when the gas load has the lowest values.

The optimal schedule of the cool system is depicted in Fig. 7. It can be seen that the AC is operated over the entire horizon in case of real-time because the AC provides cool power more economic than the EC. However, at the hour 20 in the day ahead the AC is not operated because the thermal load has the highest value. Therefore, the EC provides the cool load at this hour. It also can be seen that the EC is operated fewer hours than the AC, where EC is committed when the heat load is high to supply the rest of the cool load.

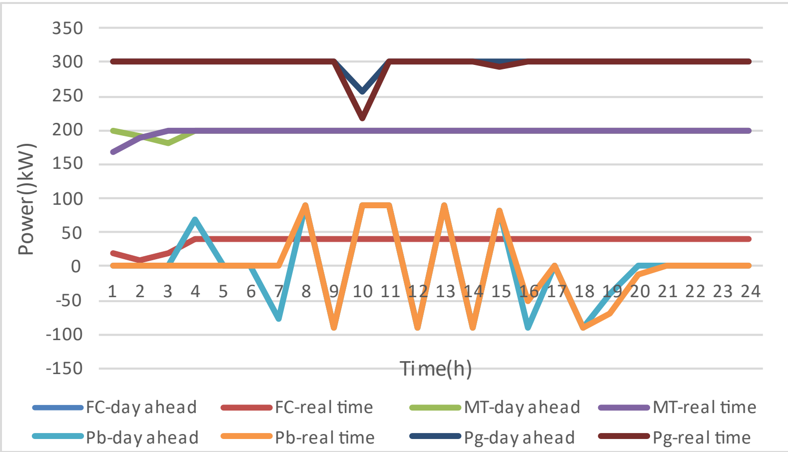


Fig. 4. Optimal schedule of the electric system.

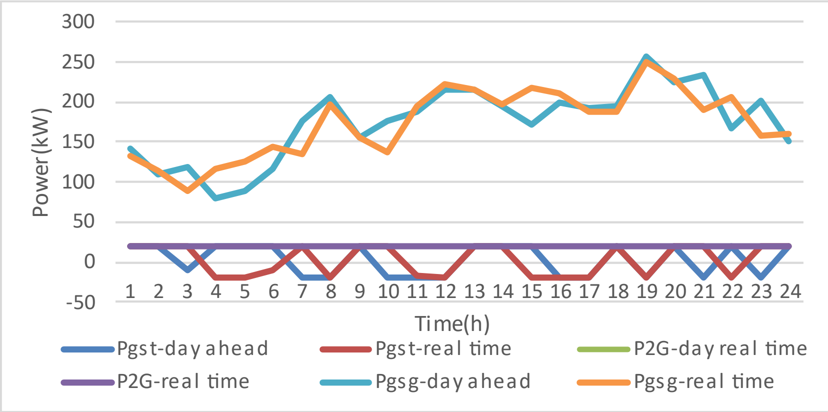


Fig. 5. Optimal schedule of the heating system.

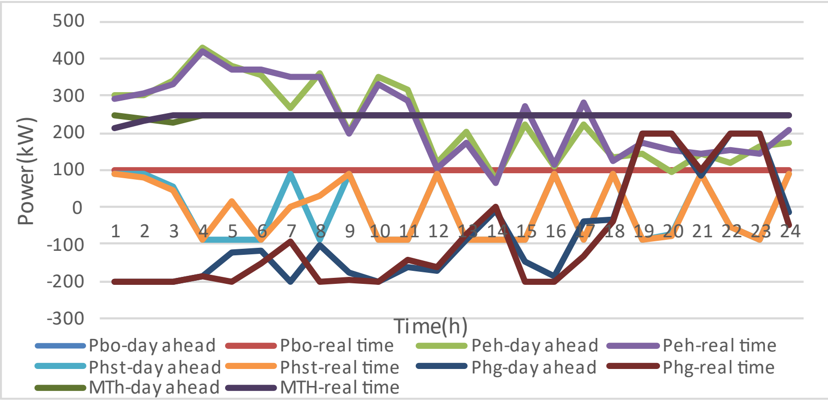


Fig. 6. Optimal schedule of the gas system.

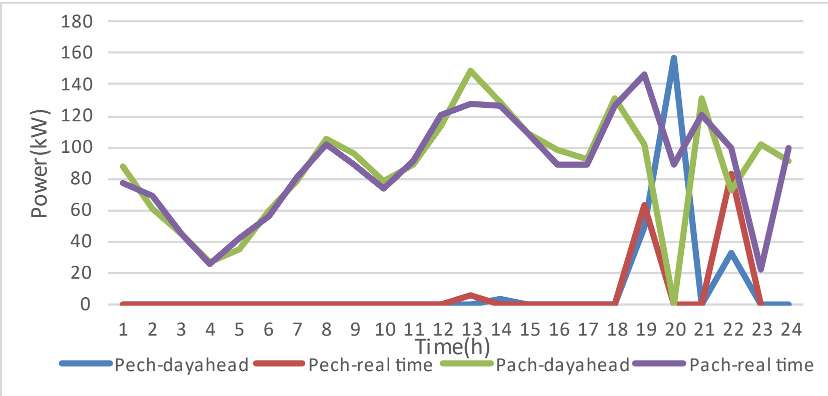


Fig. 7. Optimal schedule of the cooling system.

Figure 8 shows the hourly revenue, expense, and profit of the system. It can be noticed that the highest profit and revenue occurs at hour 10 for both real-time and day-ahead because. This is because the highest electric open market price and the high exchange heat price with utility grid are at this hour. Where, the system sells the electricity and heat power to the consumers by the open market price. It also can be seen that the highest expense occurs at hour 13 because the electric load has the highest value, and the gas and cool loads have high values. Besides, the lowest profit and revenue occurs ant hour 6 when the electric and heat price has low values.

The total profit per day is 2615.9 $ and 2631.6 $ for the day ahead and real-time respectively. By comparing the results of this paper with aforementioned paper in the introduction, it can be observed that the method which is used in this work can tackle the uncertainties that come from renewable generation, loads , and open market price efficiently and find feasible solution.

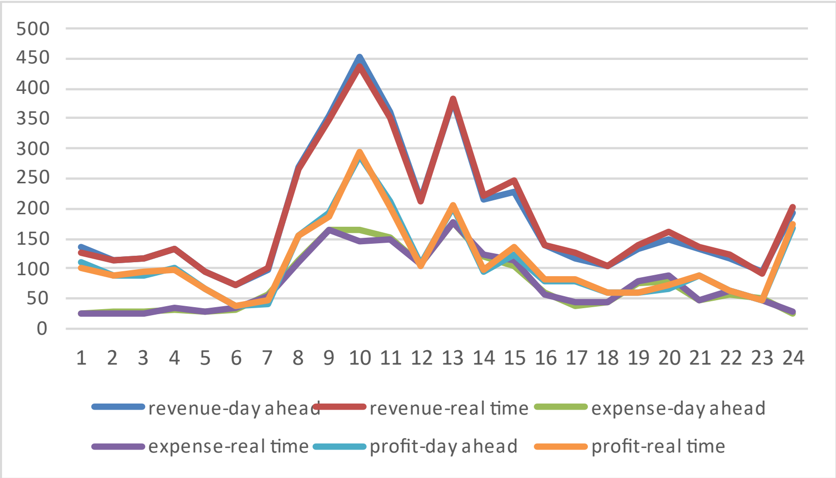


Fig. 8. The hourly revenue, expense, and profit for day-ahead and real-time.

8. Conclusion

This paper proposes an energy management system to maximize the profit of the integrated CPGHCS, which is supplied different loads. The model of the problem includes the P2G technology, electric power system, heat system, cool system, and gas system. The exchanging energy between subsystems improve the operation of entire system and increase the profit. The environmental cost is considered at the expense of the proposed approach. FERHT is employed to tackle the uncertainties that evolve from the renewable generation and load demands. The simulation results reveal that the RHT can tackle the uncertainties efficiently during real-time operation. Besides, the exchanging electric, heat, gas energy with the utility grid helps to mitigate the impacts of uncertainties and increase the profit of the system.

The transformation of the energy from form to other contributes to increase the profit of the system and keep the environment safe. The P2G system reduces the emission of CO_2, and it is used for providing SNG. This protects the environmental from damage and increases the profit of the system. The energy storage devices are scheduled to maximize the profit of the system.

Nomenclatures

$C_L(t)$	Cooling load, kWh
C_d	Battery degradation cost, $/kWh

Nomenclatures

C_j	Expense of emission of j^{th} GHG, €/kg
COP_{ac}	Coefficient of performance AC
COP_{ec}	Coefficient of performance EC
$E_{j,FC}$	Emission amount of j^{th} GHG from the FC, kg/kWh
$E_{j,MT}$	Emission amount of j^{th} GHG from the MT, kg/kWh
$G_L(t)$	Gas load, kWh
$G_{gs,ch}$	Gas stored, kW
$G_{gs,dis}$(t)	Gas released, kW
$H_{ac}(t)$	Heat which is supplied to AC
$H_{gb}(t)$	Heat generated by GB, kWh
$H_{eh}(t)$	Heat generated by EH, kWh
$H_{hs,ch}(t)$	Heat stored, kWh
$H_{hs,dis}(t)$	Heat discharged, kWh
$H_L(t)$	Heat load, kWh
$H_{MT}(t)$	Heat generated by MT, kWh
H_U(t)	Trading heat with the utility grid, kWh
L_{NG}	Low heating value of natural gas, kWh/m^3
$P_{bch}(t)$	Charging power of the battery, kWh
$P_{bdis}(t)$	Discharging power of the battery, kWh
$P_{CO_2}(t)$	CO_2 (m^3/h) consumption for SNG production
$P_{eH_2}(t)$	Electrical power (kWh) consumed at time t for producing H_2
$P_{FC}(t)$	Electrical power of FC, kWh
$P_L(t)$	Electrical load, kWh
$P_{MT}(t)$	Electrical power of MT, kWh
$P_{U,P}(t)$	Trading power with the upstream grid, kWh
$P_{ec}(t)$	Electric power which is supplied to EH
$P_{eh}(t)$	Consumed by EH, kWh
p_g	Price of the natural gas($/m^3
$P_{SNG}(t)$	production of SNG, m3 /h
$p_U(t)$	Exchanging power price with the utility grid, $/kWh
$p_{U,H}(t)$	Exchanging heating price with the utility grid, $/kWh
S_c, S_d	Price of the start-up and shutdown cost of the DG, FC, and MT, $/kWh
$U_{FC}(t)$	On/off state of the FC
$U_{MT}(t)$	On/off state of the MT
$W_b(t)$	State of charge of the battery at time t
$W_{gs}(t)$	State of charge of the gas storage at time t
$W_{hs}(t)$	State of charge of the heat storage at time t

Greek Symbols

$\delta(t)$	On/off state of the DG
$\delta_{FC}(t)$	On/off state of the FC
$\delta_{MT}(t)$	On/off state of the MT
η_{eh}	Efficiency of EH
η_{FC}	Efficiency of FC
η_{H_2}	Efficiency of H_2 production

Nomenclatures

η_{gb}	Efficiency of GB
η_{ch}	Efficiency of charging power
η_{dis}	Efficiency of discharging power
$\eta_{hs,ch}$	Efficiency of charging heat
$\eta_{hs,dis}$	Efficiency of discharging heat
η_{MT}	Efficiency of MT
δ_1	Heat loss factor of MT
δ_{hr}	Efficiency of heat recovery

Abbreviations

CHP	Combined heat power
FERHT	Fixed end receding horizon technique
CPGHCS	Combined electric power, natural gas, heat, and cool system
NG	Natural gas
P2G	Power to gas technology

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