Optimization of Operating for CCHP Based on Energy and Economical Considerations

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Abstract:

The objective of current study is to address the problem of energy management and optimal operation of CCHP system which consists of gas engines, heat recovery direct-fired machines, electric chillers and gas boilers. A model is proposed for optimizing operation of CCHP system with the objective functions is energy cost. Optimal operational strategies that minimum the overall cost of energy are given in different load demands. The result gives the distribution of electricity, heating and cooling loads for each subsystem. The on-off state and load fraction of each equipment during the optimal operation are presented as well. The primary energy utilization for each optimal operational strategy is concerned and discussed also.

Keywords:

Optimization, CCHP system, Energy cost, Primary energy utilization, Gas engine.

1. Introduction

Combined cooling, heating and power system (CCHP) is getting more attention for its energy saving, energy supply security, emission control and the economy, etc. [1-7]. CCHP system have been introduced successfully in China into various types of buildings such as hotels, offices, schools and hospitals in recent years for its meeting simultaneously cooling, heating and power demands for a variety of residential, industrial and commercial installations. The definition and benefits of CCHP systems are clarified by D.W. Wu and R.Z. Wang [8], then the characteristics of CCHP technologies are presented as well. The worldwide status quo of CCHP development is also briefly introduced by dividing the world into four main sections: the US, Europe, Asia and the Pacific, and rest of the world in their research. A typical CCHP system has many operational policy alternatives to satisfy the energy demand, because the supply and the demand of both electricity and thermal energy are complexly connected to each other. All these potions make energy management of the CCHP system a very complex but important task. It becomes obvious that in order to realize the greatest cost savings when operating a CCHP system, optimization must be performed.

CCHP systems can be optimized based on different optimization criterion such as: operation cost reduction, energy savings or minimum environmental impact. Optimization models of CCHP have been proposed by many researchers. Liu M et al. [9] proposed a new CCHP system operational strategy based on the electric cooling to cooling load ratio, which describes the portion of the cooling load that is supplied by the electric chiller, and they used an optimization algorithm to determine the optimal power generation unit capacity. X.Q. Kong et al. [10] proposed a simple linear programming model to determine the optimal strategies that minimize the energy cost for the CCHP system, which consists of a gas turbine, an absorption chiller and a heat recovery boiler. It is shown that the optimal operation of this system is dependent upon load conditions to be satisfied. In view of energy cost, it is shown that sometimes it may not be optimal to operate the turbine. This is the case when the electric-to-gas cost ratio is very low. A model in terms of cheaper operational cost and smaller CO_2 emission has been proposed by Bracco S et al. [11], which has a general validity even if to the system in an urban area in different cities. Moran et al. [12] presented results from CCHP systems simulations using natural gas and diesel internal combustion engines as prime movers. The system efficiency for cooling months was found to reach values up to 80% with economic feasibility highly dependent on fuel prices. P.J. Mago et al. [13] analyzed performance of CCHP and CHP systems in the two main operational modes FEL and FTL, based on primary energy consumption (PEC), operation cost, and carbon dioxide emissions (CDE) for different climate conditions. Their results show that CCHP and CHP systems operated FTL reduce the PEC for all the evaluated cities. On the other hand, CHP systems operated FEL always increases the PEC. The only operation mode that reduces PEC and CDE while reducing the cost is CHP-FTL. P.J. Mago and L.M. Chamra [14] studied the optimization of CCHP system based on energy, economical, and environment considerations. Their results show that CCHP systems operating using any of the optimization criteria have better performance than CCHP systems operating without any optimization criteria. Hybrid electric-thermal load has been mentioned as a good alternative for CCHP systems operation since it gives good reduction of PEC, cost, and CDE. X.Q. Kong et al. [15] investigated energy management and optimal operation of micro-CCHP consists of a gas engine, an adsorption chiller, a gas boiler, a heat exchanger and an electric chiller. It is shown that energy management and optimal operation of the micro-CCHP system is dependent upon load conditions to be satisfied and energy cost. In view of energy cost, it would not be optimal to operate the gas engine when the electric-to-gas cost ratio (EGCR) is very low. With higher EGCR, the optimum operational strategy of the micro-CCHP system is independent of energy cost. For the primary energy utilization, Hui Li et al. [16] presented a static calculation methodology for evaluating the primary energy consumption for CCHP and separate productions. Fuel energy saving ratio (FESR) definition and the boundary conditions that have to be met by CCHP systems for being energy saving to separate productions are given. Fang et al. [17] proposed an optimal operational strategy based on FEL and FTL strategies that depends on an integrated performance criterion (IPC). Usingthe proposed strategy, the operation of the CCHP system is divided into different regions by one to three border surfaces estimated by the CCHP system energy requirements and the IPC. The IPC simultaneously takes the reduction of primary energy consumption, operational cost and CO_2 emissions into account.

To summarise, the operational optimization of CCHP has been studied from different angles by many researchers, however, the operation of each equipment of CCHP in the optimal strategy has been referred relatively scarce, which is the key to direct the operation of the system. In this paper, the optimization of CCHP which integrates gas engines, heat recovery direct-fired machines (HRDF), electric chillers and gas boilers is studied for lowest energy cost. A model is proposed by taking the variation of all main devices under different load conditions into account. Given the particular electrical, heating and cooling load conditions, a set of optimal values of all the operational variables for each hour in a day, which produces the lowest energy costs, would be determined. The result gives the distribution of electricity, heating and cooling loads for each subsystem. The on-off state and load fraction of each equipment during the optimal operation are presented as well. Since the primary energy utilization and energy cost cannot achieve the optimum simultaneously [18], the primary energy utilizations under the economical optimum operational strategies are analyzed in this study.

2. Development of the model

2.1. CCHP system

The CCHP system integrates gas engine generators, heat recovery direct-fired machines (HRDF), electric chillers and gas boilers. Schematic of the CCHP system is shown in Fig. 1. From the figure it can be seen that natural gas is supplied to the engine generator to meet the electricity demand. The waste heat from the gas engine includes two parts: the high-temperature exhaust gas and the high-temperature jacket water. The high-temperature exhaust gas and part of jacket water are recovered by the HRDF, which can supply heating or cooling in different working modes, but not simultaneously. The HRDF also can be driven by natural gas besides exhaust gas and jacket water. The high- temperature jacket water is divided between the HRDF and the heat exchanger that helps to accommodate the heating load. The electricity from the outside power grid and the electric chiller and the gas boiler are used as optional devices to help meet the electric load, cooling load and heating load, respectively.

2.2. CCHP system model

2.2.1. Objective function and variables

The lowest energy cost that is the sum of the costs of purchased natural gas and purchased electricity from the grid is the objective function of this model. The system mode includes several operational variables: the on-off variables of the main devices (engine generator, HRDF, electric chiller and gas boiler), S, the jacket water flow split, R_{jw}. S=1 means the device is on, S=0 means the device is off. R_{jw} is the operational parameter that apportions the hot jacket water flow between the HRDF and the heat exchanger. R_{jw} =0 means that all of the hot jacket water is provided to the heat exchanger, R_{jw} =1 means that all of the hot jacket water is provided to the HRDF.

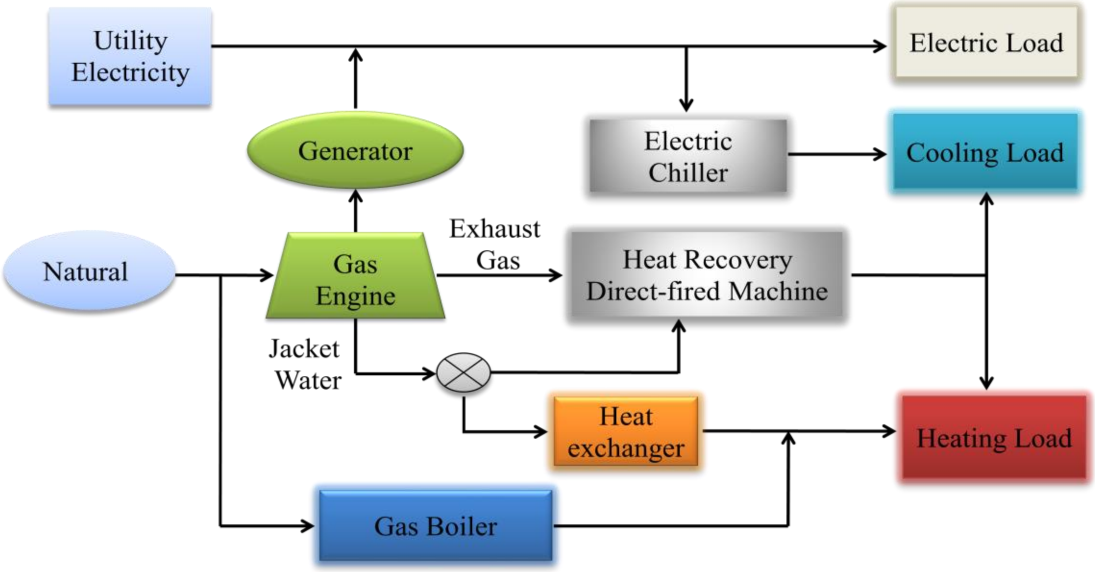


Fig. 1. Schematic of the CCHP system.

In the following analysis, the unit of measurement for the natural gas is m^3/h while the unit for power terms is kW, including electric, cooling and heating loads. The unit of run time is in hours and the heat value of natural gas is kWh/m^3. The cost rates of natural gas and electricity have units of RMB￥/m^3 and RMB￥/kWh, respectively. All costs are in RMB (1 US$ = 6.23 RBM￥).

2.2.2. CCHP system model analysis

First of all, the loading fraction of the device is introduced, which can be calculated as the ratio of actual power to rated power of the device, can be expressed as

$$F_{engine}=\frac{E_{engine-actual}}{E_{engine-rated}},\ F_{HRDF}=\frac{Q_{HRDF-actual}}{Q_{HRDF-rated}},\ F_{ec}=\frac{Q_{ec-actual}}{Q_{ec-rated}},\ F_{boiler}=\frac{Q_{boiler-actual}}{Q_{boiler-rated}} \qquad (1)$$

For the gas engine generator, the on-off of the engine that depends on the loading fraction is determined as follows

$$S=\begin{cases}0 & 0\le F<c\\ 1 & c\le F\le 1\end{cases} \qquad (2)$$

where c is a parameter from 0 to 1 which is determined by the type of the device. The relation between engine gas input power and loading fraction can be estimated as

$$P_{gas\ input} = \begin{cases} f_1(F_{engine}) & S_{engine} = 1 \\ 0 & S_{engine} = 0 \end{cases} \quad (3)$$

It should be noticed that, for different equipment, the *f* will be different, which describes the relationship between the power input (or output) and corresponding equipment load fraction . So, the amount of natural gas required by the engine is calculated as

$$V_{engine} = \frac{P_{gas\ input}}{HV_{ng}} \quad (4)$$

The jacket water thermal output that varies with different load fraction can be estimated as

$$P_{jw} = \begin{cases} f_2(F_{engine}) & S_{engine} = 1 \\ 0 & S_{engine} = 0 \end{cases} \quad (5)$$

The exhaust gas thermal output that varies with different load fraction can be estimated as

$$P_{eg} = \begin{cases} f_3(F_{engine}) & S_{engine} = 1 \\ 0 & S_{engine} = 0 \end{cases} \quad (6)$$

The HRDF can supply heating in heating working mode, and cooling in cooling working mode. The high-temperature exhaust gas and part of the hot jacket water are recovered by HRDF, and the natural gas is supplied as additional thermal input. In the cooling mode, the additional natural gas required by HRDF can be estimated as

$$V_{HRDF-cooling} = \frac{\dfrac{\min(Q_{HRDF-cooling-rated}, Q_{cooling})}{COP_{HRDF-cooling}} - (P_{eg} + R_{jw}P_{jw})}{HV_{ng}} \quad (7)$$

where $COP_{HRDF\text{-}cooling}$ is the coefficient of performance of HRDF in cooling working mode, which would be different under different loading fractions.

$$COP_{HRDF-cooling} = \begin{cases} f_4(F_{HRDF-cooling}) & S_{HRDF} = 1 \\ 0 & S_{HRDF} = 0 \end{cases} \quad (8)$$

For HRDF in the heating working mode, the additional natural gas required by HRDF can be estimated as

$$V_{HRDF-heating} = \frac{\dfrac{\min(Q_{HRDF-heating-rated}, Q_{heating})}{COP_{HRDF-heating}} - (P_{eg} + R_{jw}P_{jw})}{HV_{ng}} \quad (9)$$

$$COP_{HRDF-heating} = \begin{cases} f_5(F_{HRDF-heating}) & S_{HRDF} = 1 \\ 0 & S_{HRDF} = 0 \end{cases} \quad (10)$$

The electric consumption of electric chiller is determined as the ratio of the cooling load to the coefficient of performance of the electric chiller.

$$E_{ec} = \frac{Q_{ec-actual}}{COP_{ec}} \quad (11)$$

where COP_{ec} also varies with the variation of loading fraction.

$$COP_{ec} = \begin{cases} f_6(F_{ec}) & S_{ec} = 1 \\ 0 & S_{ec} = 0 \end{cases} \quad (12)$$

One part of hot jacket water flow into a heat exchanger to help meet the heating load. The heat supplied by the heat exchanger can be estimated as

$$Q_{hex} = (1 - R_{jw}) \times P_{jw} \times \eta_{hex} \tag{13}$$

The gas boiler would start while the heat from HRDF and heat exchanger is not enough to handle the heating load. The additional heat which has to be provided by the boiler is calculated as

$$Q_{boiler-actual} = Q_{heating} - Q_{HRDF-actual} - Q_{hex} \tag{14}$$

The natural gas required by boiler can be calculated as

$$V_{boiler} = \frac{Q_{boiler-actual}}{\eta_{boiler} \times HV_{ng}} \tag{15}$$

As elucidated above, the electricity purchased from the power grid, which is calculated by subtracting the electricity generated by the gas engine from the sum of electric load, electric chiller load and pump load, can be expressed as

$$E_{purchased} = E_{load} + E_{ec} + E_{pf} - E_{engine-actual} \tag{16}$$

Where E_{pf} is the electricity required by the pump and fan of the CCHP system, which can be approximately estimated base on the cooling and heating loads [15].

$$RMB_{elec} = E_{purchased} \times t \times PR_{elec} \tag{17}$$

The cost of purchased natural gas is estimated as

$$RMB_{ng} = (V_{engine} + V_{HRDF} + V_{boiler}) \times t \times PR_{ng} \tag{18}$$

Therefore, the total energy cost is the sum of the costs of purchased natural gas and electricity, can be calculated as

$$RMB_{total} = RMB_{ng} + RMB_{elec} \tag{19}$$

The CCHP system primary energy utilization can be estimated as

$$PEU = \frac{E_{engine-actual} + Q_{cooling-hr} + Q_{heating-hr}}{V_{engine} \times HV_{ng}} \tag{20}$$

2.2.3. Model constraints

A C++ program has been developed to solve the above optimization model. Before that, several constraints should be set to ensure that the model makes sense physically.

$$0 \le F \le 1 \quad 0 \le R_{jw} \le 1 \tag{21}$$

$$V_{engine} \ge 0 \quad V_{HRDF} \ge 0 \quad E_{ec} \ge 0 \quad V_{boiler} \ge 0 \tag{22}$$

In this analysis, it is assumed that all electricity generated by the engine is used by the system. No electricity is to be sold back to the grid. By constraining the purchased electricity to a positive value, this condition is maintained

$$E_{purchased} \ge 0 \tag{23}$$

3. Case system analysis

To examine and verify the optimization model, an actual CCHP system project is introduce to be optimized by this model. The chosen actual CCHP system project is a hospital in Beijing, which consists of 2 gas internal combustion engines with rated power of 834 kW, 2 HRDFs with cooling rated power of 1454 kW and heating rated power of 1150 kW, 3 electric chillers with rated power of 1257 kW, and 2 gas boilers with rated power of 2800 kW. The hospital has electric, heating and hot water demands in winter, and electric, cooling, and hot water demands in the rest of year. The loads of the hospital for 24 hours in a typical day are shown in Fig. 2 and Fig. 3.

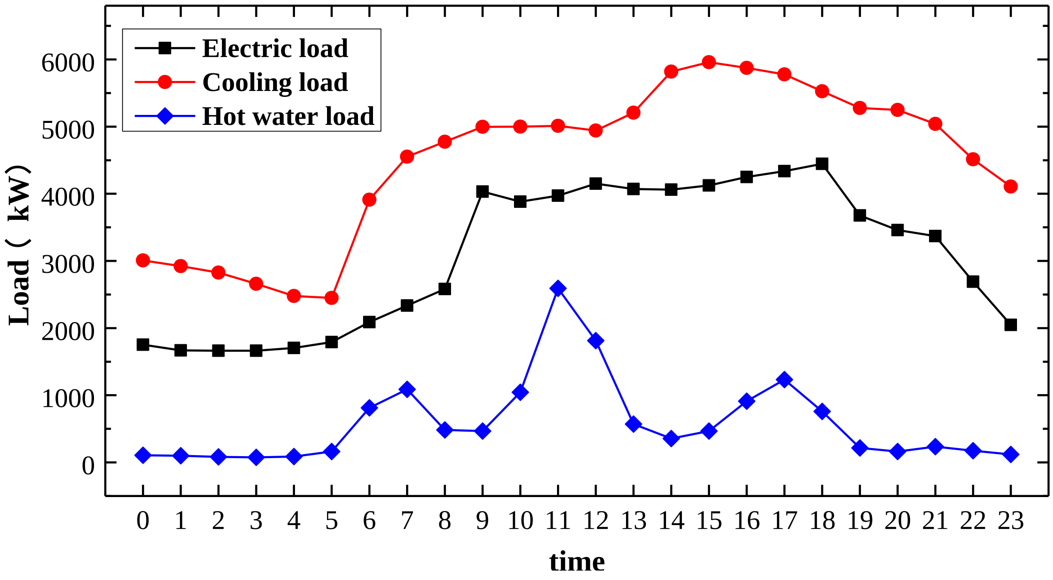


Fig. 2. Loads of the actual case in the seasons except winter.

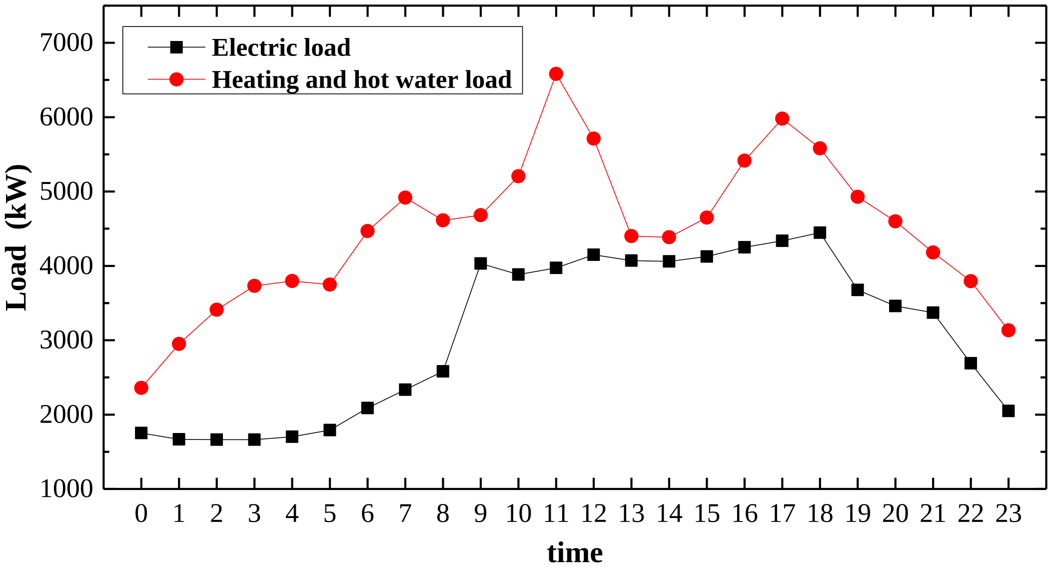


Fig. 3. Loads of the actual case in winter.

As mentioned previously, the energy output of engine varies under different load fractions. Base on the tests on site, the energy outputs of the engine have been obtained and list in Table 1.

Table 1. Energy parameters of engine at different load fractions

Load fraction F_{engine}	*1*	*0.9*	*0.8*	*0.7*	*0.6*	0.5
Energy input (kW)	2089	1897	1705	1514	1322	1131
Generated electricity (kW)	834	750	666	582	498	414
Jacket water (kW)	462	449	426	393	349	295
Exhaust gas cooled to be 180 °C (kW)	431	379	333	293	259	232

Base on the tests on site, the coefficients of performance of HRDF in cooling mode varies under different load fractions, which is list in Table 2. The coefficients of performance of HRDF in heating mode varies very slightly, so can be considered as constant as 0.85 by the tests on site.

Table 2. Coefficienst of performance of HRDF in cooling mode at different load fractions

Load fraction F_{HRDF}	*1*	*0.9*	*0.8*	*0.7*	*0.6*	*0.5*	*0.4*	*0.3*	*0.2*
$COP_{HRDF\text{-}cooling}$	1.00	1.06	1.12	1.18	1.21	1.19	1.13	1.02	0.82

Base on the tests on site, the coefficient of performance of electric chiller changes under different load fractions, which is shown in Table 3.

Table 3. Coefficients of performance of electric chiller at different load fractions

Load fraction F_{ec}	*1*	*0.9*	*0.8*	*0.7*	*0.6*	*0.5*	*0.4*	*0.3*	*0.2*
COP_{ec}	4.6	4.7	5.1	5.5	5.8	5.4	5.2	3.6	3.2

The efficiency of the gas boiler and heat exchanger can be considered as constant as 0.85 and 0.9, respectively, based on the tests on site. The function relationships f_1, f_2, f_3, f_4 and f_6 as shown in (3) , (5), (6), (8) and (12) can be determined based on the dates as shown in Tables 1 to 3. The constant c in (2) is determined to 0.5 for gas engine, 0.15 for electric chiller and HRDF base on the equipment parameters.

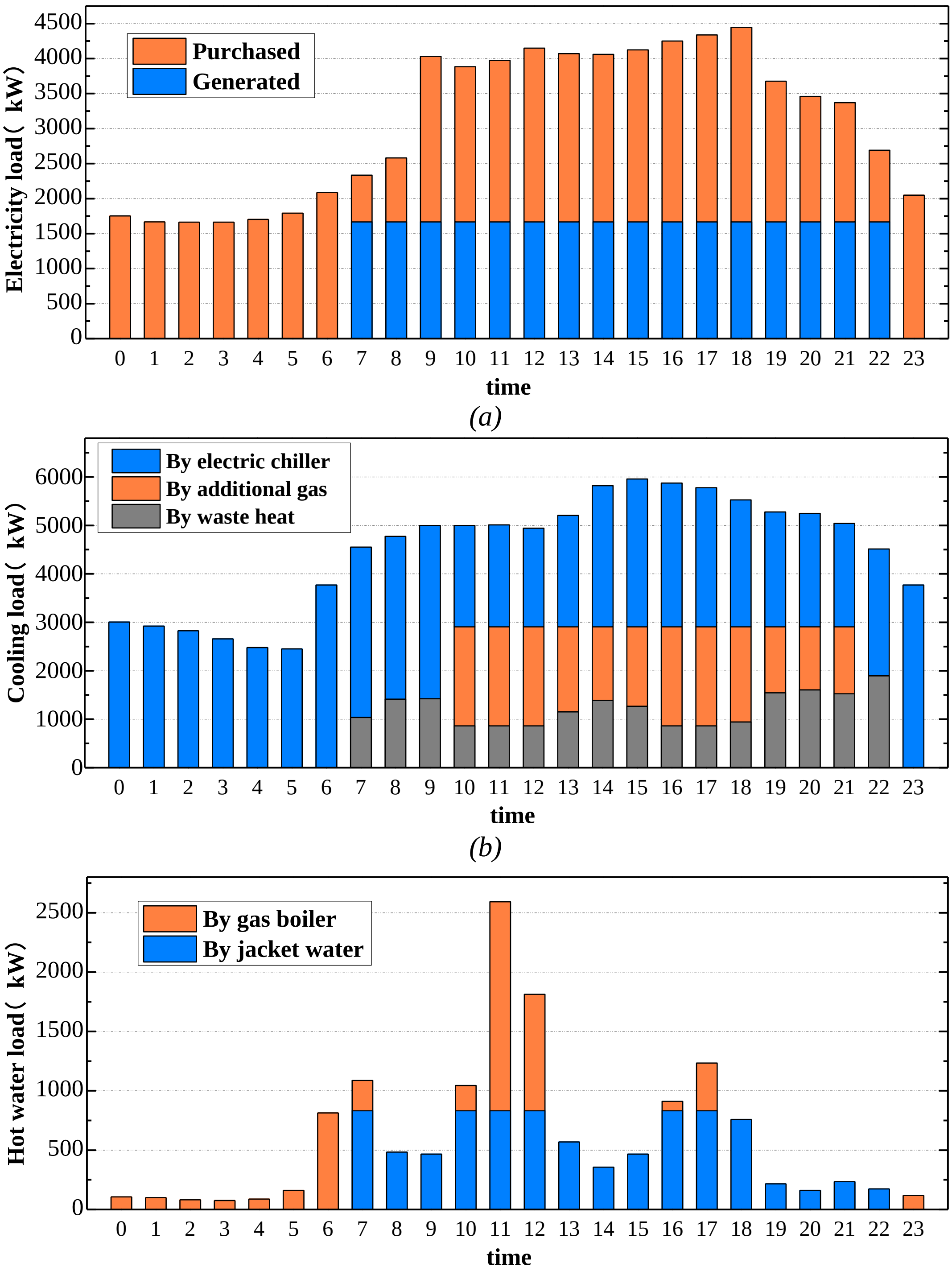
To solve the model, some parameters else are needed, such as the price and heat value of natural gas, and the price of electricity. The local price of natural gas in Beijing is 2.7 RMB￥/m^3, the heat value is 9.38 kWh/m^3, the price of electricity is divided into 4 ranges based on time, which is shown as follows: critical peak electricity price (11:00-13:00 & 16:00-17:00, just in July and August), 1.5065 RMB￥/kWh, peak electricity price (10:00-15:00 & 18:00-21:00), 1.3782 RMB￥/kWh, flat electricity price (7:00~10:00 & 15:00~18:00 & 21:00~23:00), 0.8598 RMB￥/kWh, valley electricity price (23:00~7:00 the next day), 0.3658 RMB￥/kWh.

4. Results

As mentioned above, the hospital has electric, cooling and hot water demands in the seasons except winter (cooling mode), the load characteristics and the operational conditions of equipments in the optimal operational strategy are shown in Fig. 4 and 5.

Fig. 4 (a) shows the electric load distribution in the optimal operation for 24 hours. Base on the calculation of the model, to meet the electric load, the electricity from grid is the preferred option at the time range from 23:00 to 7:00 the next day due to the lower electricity price at that time. So, the electric load is completely satisfied by the electricity from grid at valley electricity price time. And at other time, the electric load is satisfied by the engine and grid together.

The optimal assignment for the cooling load and hot water load are depicted in Fig. 4 (b) and (c). None of waste heat can be used to generate any energy because the gas engines are set to be closed from 23:00 to 7:00 the next day. The cooling load can be met by electric chillers and HRDFs. The basis of choosing the preferred equipment is the cost of the energy consumption. The cooling load is supplied by electric chillers preferentially when the gas-to-electric cost ratio is relative higher. The waste heat will be used surely as the gas engine is on. Then the HRDFs driven by additional gas and electric chillers would be chosen also base on the cost. The waste heat in Fig. 4 (b) consists of exhaust gas heat and part of jacket water heat, the anther part of jacket water is used to meet the hot water load through a heat exchanger as shown in Fig. 4(c). The rest of hot water load is satisfied by the gas boilers.



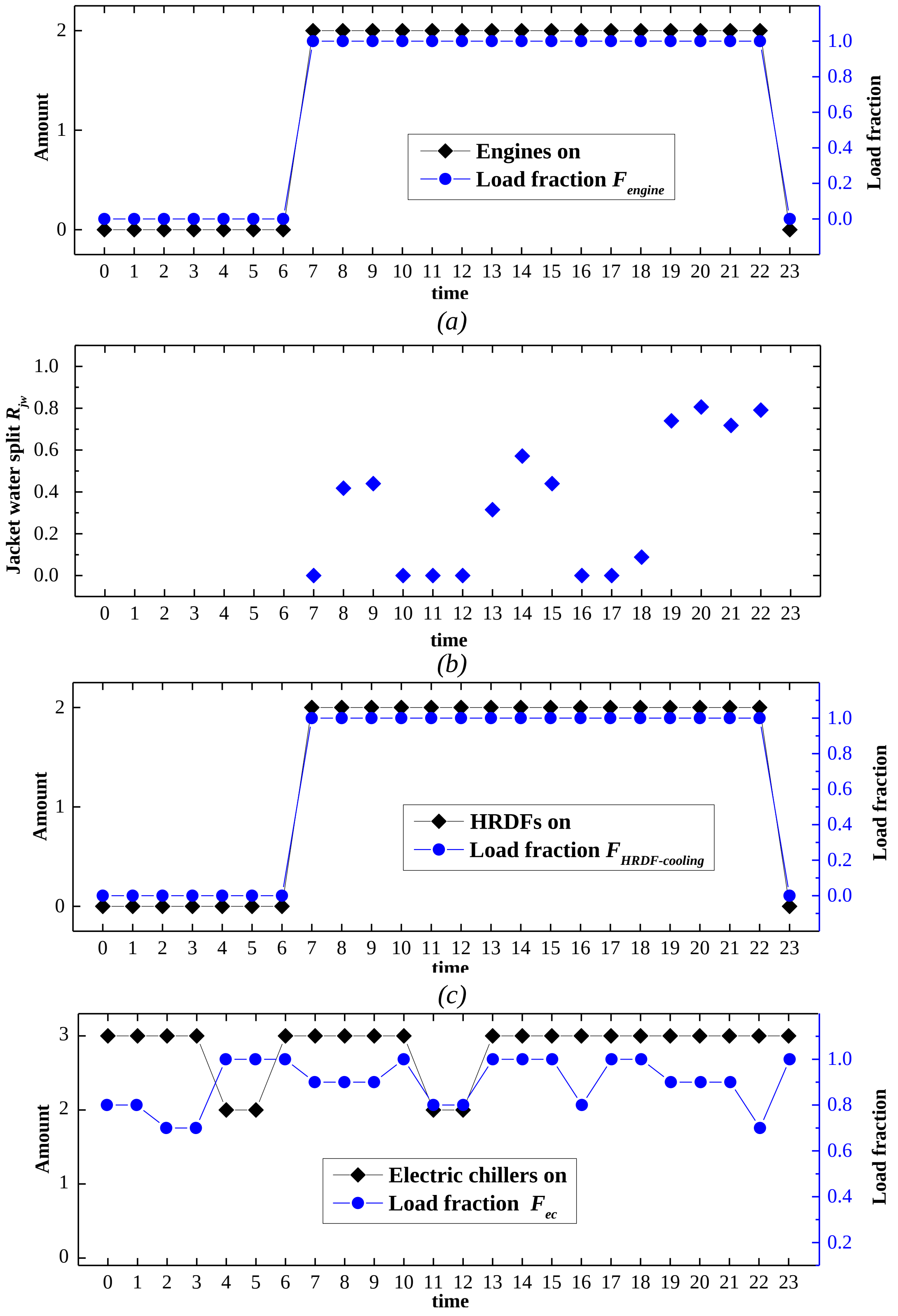
(a)

(b)

(c)

Fig. 4. Load distributions under optimal operation in cooling mode.

Base on the load distributions in Fig. 4, the operation of the equipments and the jacket water split are shown in Fig.5. The load fractions of corresponding equipments are given as well.

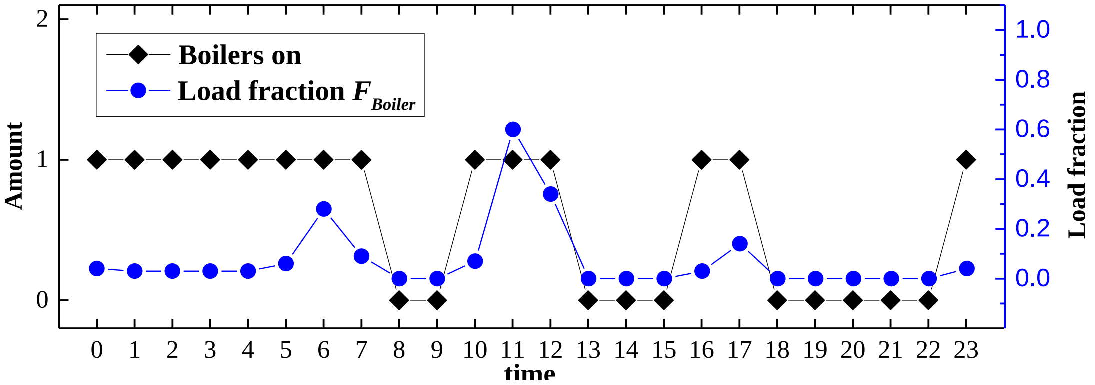

Amount
Load fraction
time
0
1
2
0.0
0.2
0.4
0.6
0.8
1.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Engines on
Load fraction F_{engine}
Jacket water split R_{jw}
HRDFs on
Load fraction $F_{HRDF\text{-}cooling}$
3
Electric chillers on
Load fraction F_{ec}

(a)

(b)

(c)

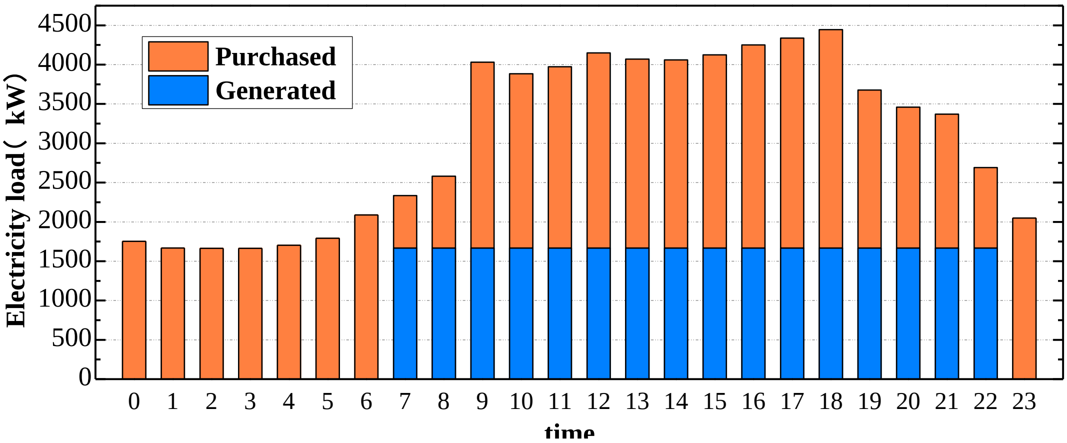
(d)



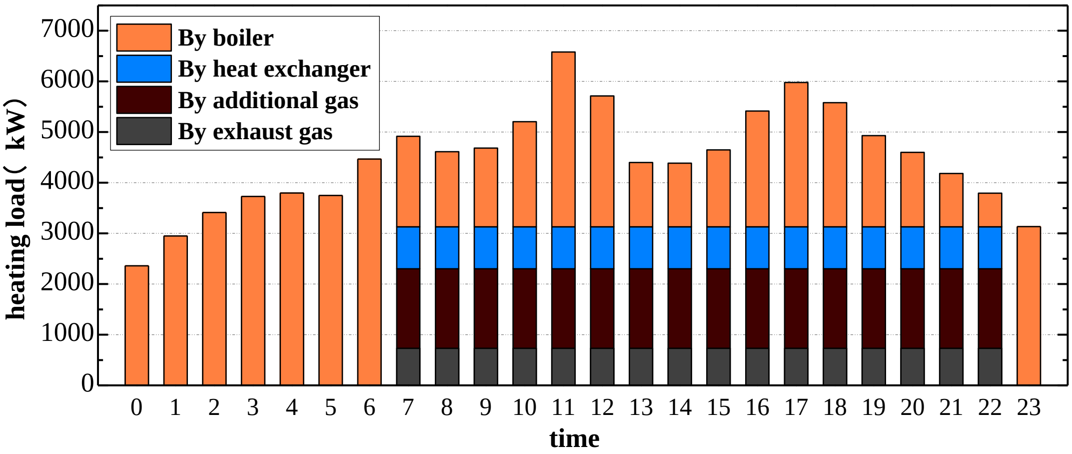
(e)

Fig. 5. The operational conditions of equipments under optimal operation in cooling mode.

The hospital has electric and heating load (including hot water load) in winter (heating mode). The optimal load characteristics are shown in Fig. 6, and the electric load characteristic is similar with that in Fig.4 (a). The heating load is completely handled by gas boiler in valley electricity price time when gas engines are kept off. The waste heating from gas engine will be used preferentially when the gas engine is kept on, and the rest of heating load can be satisfied by HRDFs driven by additional gas and gas boiler. Fig. 7 gives the operation of the equipments and the jacket water split in optimal operation strategy.

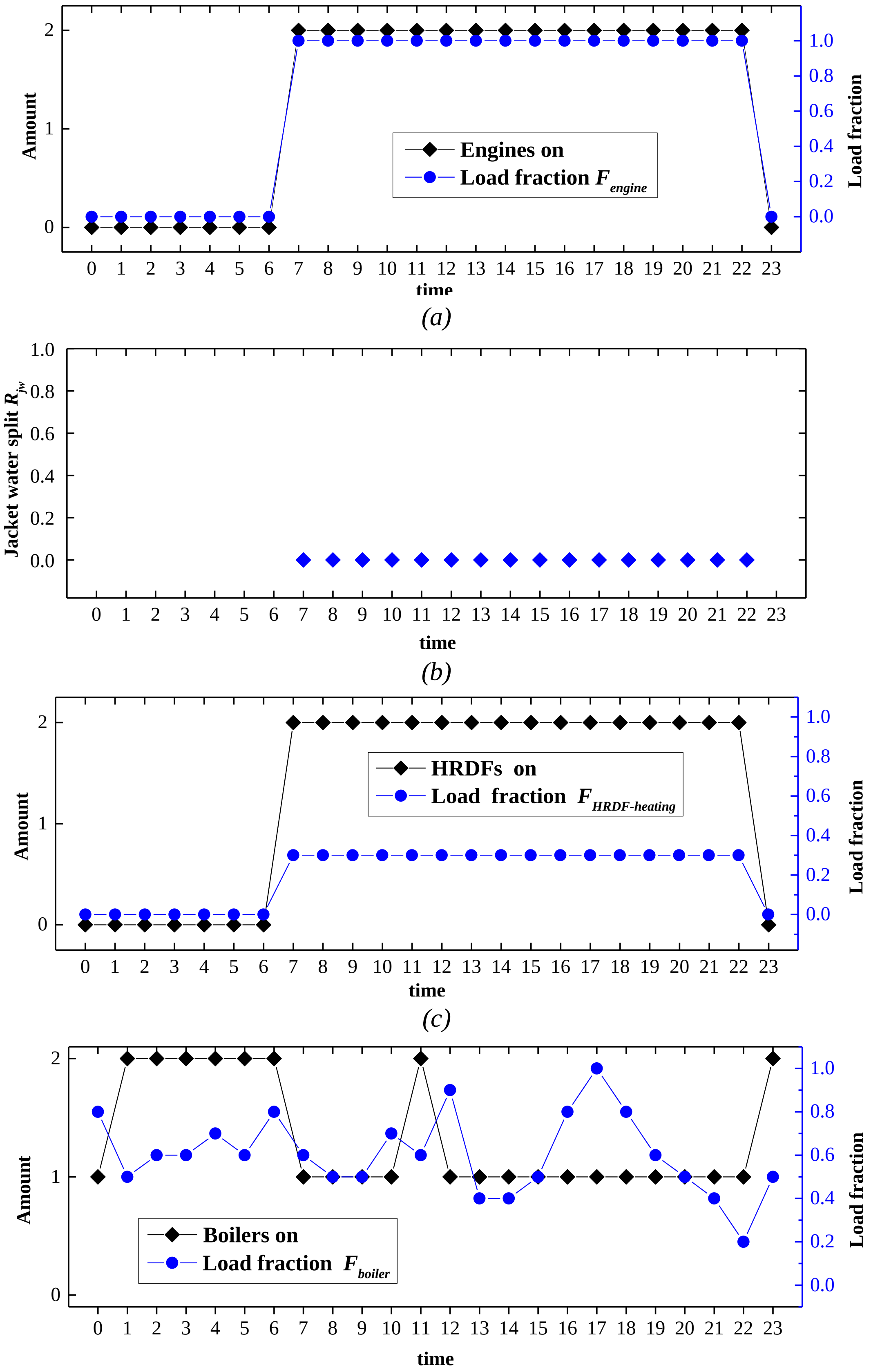


(a)



(b)

Fig. 6. Load distributions under optimal operation in heating mode.



(a)

(b)

(c)

(d)

Fig. 7. The operational conditions of equipments under optimal operation in heating mode.

As reported by [17], for a CCHP, the energy cost and the energy saving cannot reach the optimal condition simultaneously. So as to assure the energy saving for the CCHP above a certain level in the optimal operation strategy base on economical consideration, the primary energy utilizations are examined in cooling mode and heating mode, respectively, as shown in Fig. 8. It can be seen from the figure, the primary energy utilizations are above 70% for all the cases, which is acceptable.

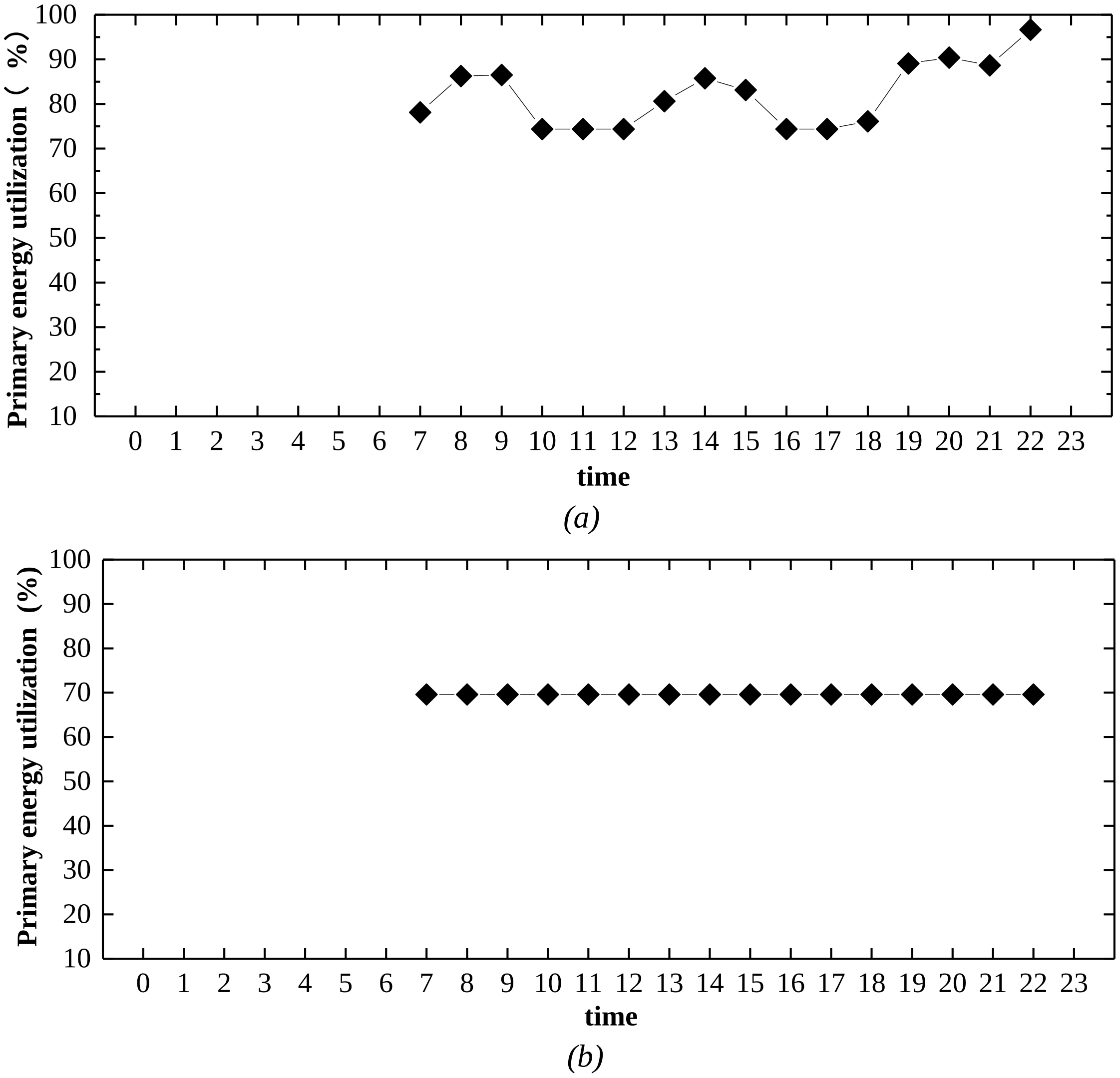


Fig. 8. The primary energy utilization of the CCHP in the optimal operation base on energy cost.

5. Conclusions

In this paper, the optimal model of operation for CCHP system which integrates gas engines, heat recovery direct-fired machines, electric chillers and gas boilers is proposed based on energy and economical considerations. The models of main devices are presented by taking the performance difference of devices under different load conditions into account. Given the particular electrical, heating and cooling load conditions, a set of optimal values of all the operational variables for each hour in a day, which produces the lowest energy costs, would be determined.

An actual CCHP case is introduced to verify the optimal model. The result shows the price of the electricity and natural gas is the key factor to determine the operational strategy of the CCHP system. The distribution of electricity, heating and cooling loads for each subsystem are obtained. The on-off state and load fraction of each equipment of the entire system for 24 hours are presented as well. So as to assure the energy saving for the CCHP above a certain level in the optimal operation strategy base on economical consideration, the primary energy utilizations are above 70% for all the cases, which is acceptable.

Acknowledgments

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Nomenclature

CCHP combined cooling, heating and power
COP coefficient of performance
c constant
E electric power, kW
F load fraction
HV heat value of natural gas, kWh/m^3
HRDF heat recovery direct-fired machine
P thermal power, kW
PEU primary energy utilization
Q heating power, kW
R split ratio
S variable of on-off of device
t time, hour
V volume, m^3

Greek symbols

η efficiency

Subscripts and superscripts

actual actual condition
cooling cooling load
elec electricity
ec electric chiller
eg exhaust gas
hex heat exchanger
heating heating load
hr heat recovery
ng natural gas
jw hot jacket water
rated rated condition
pf pump and fan

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