Residential CCHP microgrid with load aggregator: Operation mode, pricing strategy, and optimal dispatch

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**Highlights**
- A bilateral transaction mode for the residential CCHP microgrid is proposed.
- An energy pricing strategy for the residential CCHP system is proposed.
- A novel integrated demand response for the residential loads is proposed.
- Two-stage operation optimization model for the CCHP microgrid is proposed.
- Operations of typical days and annual scale of the CCHP microgrid are studied.

**Abstract**
As the global energy crisis, environmental pollution, and global warming grow in intensity, increasing attention is being paid to combined cooling, heating, and power (CCHP) systems that realize high-efficiency cascade utilization of energy. This paper proposes a bilateral transaction mechanism between a residential CCHP system and a load aggregator (LA). The variable energy cost of the CCHP system is analyzed, based on which an energy pricing strategy for the CCHP system is proposed. Under this pricing strategy, the electricity price is constant, while the heat/cool price is ladder-shaped and dependent on the relationship between the electrical, heat, and cool loads. For the LA, an integrated demand response program is proposed that combines electricity-load shifting and a flexible heating/cooling supply, in which a thermodynamic model of buildings is used to determine the appropriate range of heating/cooling supply. Subsequently, a two-stage optimal dispatch model is proposed for the energy system that comprises the CCHP system and the LA. Case studies consisting of three scenarios (winter, summer, and excessive seasons) are delivered to demonstrate the effectiveness of the proposed approach, and the performance of the proposed pricing strategy is also evaluated by annual operation simulations.

**1. Introduction**
Combined cooling, heating, and power (CCHP) systems comprise distributed units including energy generation units, energy conversion units, storage units, and renewable energy systems \[1,2\]. CCHP systems can meet various energy demands and have been used widely in hospitals, schools, and residential buildings \[3,4\]. Compared with traditional energy systems, CCHP systems realize cascade utilization of energy with higher efficiency (up to 60–80%), which bring them a promising future \[5–7\].

Operation optimization is an important issue for CCHP systems to improve their economic and environmental benefits \[8–12\]. Many researches are focused on the strategies and solution methods of the CCHP system operation. Zheng et al. \[13\] proposed a minimum distance operation strategy, which can lead to better matching performance for a CCHP system compared with following electrical load (FEL), following thermal load (FTL), and following hybrid load (FHL). Wang et al. \[14\] proposed a multi-object operation optimization model for CCHP systems, in which the average useful output and the total heat transfer area were selected as the objective functions, and the Non-dominated Sort Genetic Algorithm-II was employed to solve it.

Some factors are also considered in the operation of CCHP microgrid systems \[15,16\], e.g., house characteristics, renewable energy integration, and uncertainties. Luo et al. proposed a two-stage operation model for the CCHP microgrid that includes day-ahead scheduling stage and real-time adjusting stage \[17\]; in the real-time adjusting stage, the power of the central air condition is adjusted based on the house characteristics. Soheyli et al. applied...
### Parameters of costs and price

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{\text{gas}}$</td>
<td>heat price of natural gas (¥/kW h)</td>
</tr>
<tr>
<td>$F$</td>
<td>operation cost of CCHP system (¥)</td>
</tr>
<tr>
<td>$F_{\text{we}}$</td>
<td>operation cost of CCHP system in winter and excessive seasons (producing heating and electricity) (¥)</td>
</tr>
<tr>
<td>$F_{\text{s}}$</td>
<td>operation cost of CCHP system in summer (producing cooling and electricity) (¥)</td>
</tr>
<tr>
<td>$c_x$</td>
<td>price of x, including $c_r$, $c_e$, and $c_c$, denotes the price of cooling, heating, and electricity respectively (¥/kW h)</td>
</tr>
<tr>
<td>$c_{\text{fix}}$</td>
<td>unit fixed cost of x, including $c_r^<em>, c_e^</em>$, and $c_c^*$, denotes the unit fixed cost of cooling, heating, and electricity respectively (¥/kW h)</td>
</tr>
<tr>
<td>$c_{\text{var}}$</td>
<td>unit variable cost of x, including $c_r^{var}$, $c_e^{var}$, and $c_c^{var}$, denotes the unit variable cost of cooling, heating, and electricity respectively (¥/kW h)</td>
</tr>
<tr>
<td>$\chi$</td>
<td>profit margin of CCHP system</td>
</tr>
<tr>
<td>$C_{\text{cchp}}$</td>
<td>objective function of CCHP dispatch (¥)</td>
</tr>
<tr>
<td>$C_{\text{la}}$</td>
<td>objective function of the LA dispatch (¥)</td>
</tr>
<tr>
<td>$C_{\text{grid}}$</td>
<td>cost of exchanging electricity with the main grid of the LA (¥)</td>
</tr>
<tr>
<td>$c_{\text{buy}}$</td>
<td>cost of buying energy from CCHP system (¥)</td>
</tr>
<tr>
<td>$c_{\text{comp}}$</td>
<td>compensation for electricity-load shifting (¥)</td>
</tr>
<tr>
<td>$c_{\text{sell}}$</td>
<td>price of electricity bought from the main grid (¥/kW h)</td>
</tr>
<tr>
<td>$c_{\text{chp}}$</td>
<td>price of electricity sold to the main grid (¥/kW h)</td>
</tr>
<tr>
<td>$c_{\text{hl}}$</td>
<td>heat price of CCHP system at step I/I/II (¥/kW h)</td>
</tr>
<tr>
<td>$c_{\text{el}}$, $c_{\text{he}}$</td>
<td>cool heat price of CCHP system at step I/II/III (¥/kW h)</td>
</tr>
<tr>
<td>$\mu_c$</td>
<td>compensation factor of the shifted electrical load (¥/kW h)</td>
</tr>
</tbody>
</table>

### Parameters of CCHP system

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>length of dispatch period (h)</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>length of time interval of dispatch (h)</td>
</tr>
<tr>
<td>$P_{\text{el}}$</td>
<td>electrical output power of CCHP system (kW)</td>
</tr>
<tr>
<td>$Q_{\text{ad}}$</td>
<td>heat output power of CCHP system (kW)</td>
</tr>
<tr>
<td>$Q_{\text{cl}}$</td>
<td>cool output power of CCHP system (kW)</td>
</tr>
<tr>
<td>$P_g$</td>
<td>electrical power of gas turbine (kW)</td>
</tr>
<tr>
<td>$P_{\text{gr}, \text{min}}$, $P_{\text{gr}, \text{max}}$</td>
<td>minimum/maximum electrical power of gas turbine (kW)</td>
</tr>
<tr>
<td>$Q_{\text{gt}}$, $Q_{\text{gth}}$, $Q_{\text{ghb}}$</td>
<td>heat power of gas turbine (kW), heat power of gas boiler (kW), maximum heat power of gas boiler (kW)</td>
</tr>
<tr>
<td>$Q_{\text{he}}$, $Q_{\text{hxe}}$, $Q_{\text{hxe}}$</td>
<td>heat power of heat exchanger (kW), heat power of electrical chiller (kW), heat power of absorption chiller (kW)</td>
</tr>
<tr>
<td>$P_{\text{sel}}$, $P_{\text{dis}}$, $P_{\text{cchp}}$, $P_{\text{la}}$</td>
<td>electrical power of the LA exchanges with the main grid (kW), shifted electrical power of battery (kW), cooling/discharge power of battery (kW), state of storing/releasing of thermal tank (kW)</td>
</tr>
<tr>
<td>$W_{\text{le}}$, $W_{\text{lb}}$, $W_{\text{be}}$, $W_{\text{bb}}$, $W_{\text{lb}}$</td>
<td>charging/discharge ratio of battery, capacity of battery (kW h), energy loss rate of battery, state of charging/discharge of battery, storing/releasing heat power of the thermal tank (kW)</td>
</tr>
<tr>
<td>$W_{\text{th}}$, $W_{\text{th}}^\text{min}$, $W_{\text{th}}^\text{max}$</td>
<td>energy level of the thermal tank (kW h), minimum/maximum energy level of the thermal tank (kW h)</td>
</tr>
<tr>
<td>$C_{\text{p}, \text{cchp}}$, $C_{\text{p}, \text{la}}$, $C_{\text{p}, \text{grid}}$</td>
<td>charging/discharge ratio of the battery, capacity of thermal tank (kW h), storing/releasing ratio of thermal tank</td>
</tr>
</tbody>
</table>

### Parameters of load aggregator

<table>
<thead>
<tr>
<th>Symbol</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$K$</td>
<td>an auxiliary positive number that is big enough but less than $+\infty$</td>
</tr>
<tr>
<td>$P_{\text{buy}}$, $P_{\text{sell}}$</td>
<td>electric power that the load aggregator exchanges with the main grid (kW)</td>
</tr>
<tr>
<td>$P_{\text{buy}}, P_{\text{sell}}$</td>
<td>maximum electric power that the load aggregator exchanges with the main grid (kW)</td>
</tr>
<tr>
<td>$P_{\text{buy}}$, $P_{\text{sell}}$</td>
<td>state that the load aggregator exchanges electricity with the main grid</td>
</tr>
<tr>
<td>$\rho_{\text{el}}, \rho_{\text{ad}}$</td>
<td>auxiliary variable to determine the steps of heat demand (kW)</td>
</tr>
<tr>
<td>$\rho_{\text{he}}, \rho_{\text{he}}$</td>
<td>state of buying electricity from CCHP system</td>
</tr>
<tr>
<td>$e_{\text{el}}$, $e_{\text{el}}$, $e_{\text{el}}$</td>
<td>binaries to determine the steps of heat demand</td>
</tr>
<tr>
<td>$Q_{\text{cl}}$, $Q_{\text{cl}}$, $Q_{\text{cl}}$</td>
<td>cool power at step I/II/III that the LA buys from CCHP system (kW)</td>
</tr>
<tr>
<td>$\rho_{\text{cl}}$, $\rho_{\text{cl}}$, $\rho_{\text{cl}}$</td>
<td>$i = 1, 2, 3$, auxiliary variables to determine the steps of cool demand (kW)</td>
</tr>
<tr>
<td>$e_{\text{cl}}$, $e_{\text{cl}}$, $e_{\text{cl}}$, $e_{\text{cl}}$</td>
<td>binaries to determine the steps of cool demand</td>
</tr>
<tr>
<td>$\rho_{\text{el}}$, $\rho_{\text{el}}$, $\rho_{\text{el}}$</td>
<td>fixed electrical load of users (kW)</td>
</tr>
<tr>
<td>$e_{\text{el}}$, $e_{\text{el}}$, $e_{\text{el}}$</td>
<td>random electrical load of users (kW)</td>
</tr>
<tr>
<td>$e_{\text{el}}$, $e_{\text{el}}$, $e_{\text{el}}$</td>
<td>shiftable electrical load of uses (kW)</td>
</tr>
<tr>
<td>$e_{\text{el}}$, $e_{\text{el}}$, $e_{\text{el}}$, $e_{\text{el}}$</td>
<td>electrical load shifted in and out (kW)</td>
</tr>
</tbody>
</table>

### Other parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>thermal resistance of the house shell ($^\circ\text{C}/\text{kW}$)</td>
</tr>
<tr>
<td>$C_{\text{air}}$</td>
<td>heat capacity of air (kW h/$^\circ\text{C}$)</td>
</tr>
<tr>
<td>$T_{\text{ini}}, T_{\text{out}}$</td>
<td>indoor/outdoor temperature of users ($^\circ\text{C}$)</td>
</tr>
<tr>
<td>$T_{\text{g}}, T_{\text{h}}$</td>
<td>optimal human comfort indoor temperature ($^\circ\text{C}$)</td>
</tr>
<tr>
<td>$T_{\text{t, \text{min}}}$, $T_{\text{t, \text{max}}}$</td>
<td>allowable minimum/maximum indoor temperature ($^\circ\text{C}$)</td>
</tr>
<tr>
<td>$\Delta T_{\text{max}}$, $\Delta T_{\text{min}}$</td>
<td>maximum difference between the actual indoor temperature and optimal indoor temperature ($^\circ\text{C}$)</td>
</tr>
<tr>
<td>$Q_{\text{air}}$</td>
<td>heat power that the load aggregator supplies to end users for indoor temperature (kW)</td>
</tr>
<tr>
<td>$Q_{\text{lair}}$, $Q_{\text{lair}}$, $Q_{\text{lair}}$</td>
<td>forecasted heat demand for maintaining the indoor temperature (kW)</td>
</tr>
<tr>
<td>$Q_{\text{c}}, Q_{\text{c}}, Q_{\text{c}}$</td>
<td>minimum/maximum heat power of x, x denotes gt, hr, ac, and he</td>
</tr>
</tbody>
</table>
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