# COGENERATION AND HEAT EXCHANGER CONTROL SYSTEM BASED ON CLEAN ENERGY

by

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*Combined cooling, heating, and power systems have received widespread attention for their high efficiency and clean characteristics. The combined cooling, heating, and power system will join the cogeneration system as clean energy and renewable resource of solar energy, further alleviating the energy crisis and environmental pollution problems. To improve the stability of the distributed power grid connection, the article designs a photovoltaic battery system that can smooth the output power and combines it with the traditional combined cooling, heating, and power system to build a comprehensive cogeneration system. Under the two operating modes of thermal follow, and electric follow, considering the impact of electric vehicle charging load, two environmental cost and life cycle cost indicators are evaluated.*

Key words: *photovoltaic battery system, power system, exchanger control system, mode evaluation*

## Introduction

In recent years, with the rapid development of the national economy, my country's energy demand has also increased. Compared with developed countries such as the USA, my country's energy utilization rate is low, which has led to increasingly serious problems such as energy crisis and environmental pollution. Adding solar energy to the cogeneration system can also alleviate the fossil energy crisis to a certain extent. Electric vehicles have received widespread attention from society because of their environmental protection, energy-saving, and economic characteristics.

Some scholars have designed a combined cooling, heating, and power systems (CCHP) system driven by an internal combustion engine and integrated solar energy. Based on the life cycle method, the internal combustion engine's capacity and the PV system's capacity are optimized. Some scholars have designed a CCHP combined with small biomass and biogas. The system also considers energy, environment, and economy to carry out multi-objective optimization design of the system. Some scholars combine the CCHP system with the energy storage system to smoothing the internal combustion's output power fluctuation engine [1].

This paper designs a PV battery system that can smooth solar energy output and combines the PV battery system with the traditional CCHP system driven by natural gas. The article considers the influence of electric vehicle charging load and designs a comprehensive CCHP

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system. Under the two operating modes of thermal, follow (FTL) and electric follow (FEL), the operating mode of the established system is evaluated based on environmental cost and full life cycle cost (LCC).

## Photovoltaic battery system

Solar energy is an uncontrollable distributed power source, and its power output is always fluctuating. The use of battery smoothing and solar panel output can reduce solar power output randomness and provide a distributed power grid connection. The PV battery system studied in this paper uses solar panels' PV effect to convert light energy into electrical energy and output. When the solar panels' power generation is greater than the electric vehicle's charging load demand, the battery is charged [2].

### *Mathematical model of the photovoltaic system*

The electric power expression of the solar panel:

$$P_{\mathrm{PV}}(t) = P_{\mathrm{STC}} \frac{G(t)}{G_{\mathrm{STC}}} \{1 + k[T(t) - T_{\mathrm{STC}}]\} \tag{1}$$

$$T(t) = T_{\mathrm{air}}(t) + 0.0138[1 + 0.031 T_{\mathrm{air}}(t)](1 - 0.042 V_{\mathrm{wind}}) G(t) \tag{2}$$

where $P_{\mathrm{PV}}(t)$ [kW] is the power emitted by the solar cell per hour, $G(t)$ [kW] – the hourly light intensity, $P_{\mathrm{STC}}$ [kW] – the rated output power of the solar cell, $G_{\mathrm{STC}}$ and $T_{\mathrm{STC}}$ [kWm$^{-2}$] – the light intensity and the solar cell temperature (take 25 °C), $k$ – the temperature coefficient, $T(t)$ – the surface temperature of the solar cell, $T_{\mathrm{air}}(t)$ – the ambient temperature, and $V$ – the wind speed [3].

### *Mathematical model of battery*

#### *Battery charge and discharge power model*

The paper uses lead-acid batteries as energy storage media, and the expression of the remaining power during charging and discharging is shown.

Charging process:

$$E_{ba}(t) = (1 - \sigma) E_{ba}(t-1) + P_{ba}(t) \Delta t \eta_c \tag{3}$$

$$E(t) = (1 - \sigma) E(t-1) - \frac{P_{ba}(t) \Delta t}{\eta_{\mathrm{disc}}} \tag{4}$$

where $E_{ba}(t)$ [kWh] is the remaining power of the battery after the end of the $t$ period, $\sigma$ [%h$^{-1}$] – is the self-discharge rate of the battery, and $P_{ba}(t)$ [kW] – the charge and discharge power of the battery in t period.

#### *Battery charging and discharging power constraints*

The maximum allowable charge and discharge power of the battery at time $t$ is determined by its own charge and discharge characteristics and the remaining power at time $t$:

$$P_{ba\_\mathrm{limit}\_c}(t) = \min \left\{ P_{ba\max\_c}, \frac{E_{ba\max}(1 - \sigma) E_{ba}(t-1)}{\eta_c \Delta t} \right\} \tag{5}$$

$$P_{ba\_\mathrm{limit}\_dis}(t) = \min\left\{P_{ba\max\_dis'} \frac{[(1-\sigma)E_{ba}(t-1) - E_{ba\min}]\eta_{dis}}{\Delta t}\right\} \tag{6}$$

where $P_{ba\_\mathrm{limit}\_c}(t)$, $P_{ba\_\mathrm{limit}\_dis}(t)$[kW] is the maximum allowable charge and discharge power at time $t$, $P_{ba\max\_c}$, $P_{ba\max\_dis}$ [kW] – the rated maximum charge and discharge power of the battery, respectively, and $E_{ba\max}$, $E_{ba\max\mathrm{n}}$ – the upper and lower limits of the battery power constraints.

*Calculation of battery capacity*

The battery capacity calculation:

$$C_{ba} = \frac{e_{\max}T}{V_{\mathrm{DC}}\eta_1\eta_2 SK} \tag{7}$$

$$e_k = u - y_k$$
$$u = \frac{1}{k}\sum_{k}^{1} y_k \tag{8}$$

where $C_{ba}$ is the installed capacity of the battery, $e_{\max}$ – the absolute value of the maximum compensation power, $T$ – the number of days of self-sufficiency, $V_{\mathrm{DC}}$ – the nominal voltage of the DC bus, $\eta_1$ – the inverter efficiency, $\eta_2$ – the battery charge and discharge efficiency, $S$ – the depth of discharge, $K$ – the temperature correction coefficient, $y_1$ – the actual output power of the solar panel in each period, and $u$ – the expected output power of the solar panel [4].

*Output power curve of the photo-voltaic battery system*

According to eqs. (3)-(10), the PV battery system's output power curve is obtained, and the 24 hours of a particular day in January of a year is selected as an example, and the power curve is shown in fig. 1.

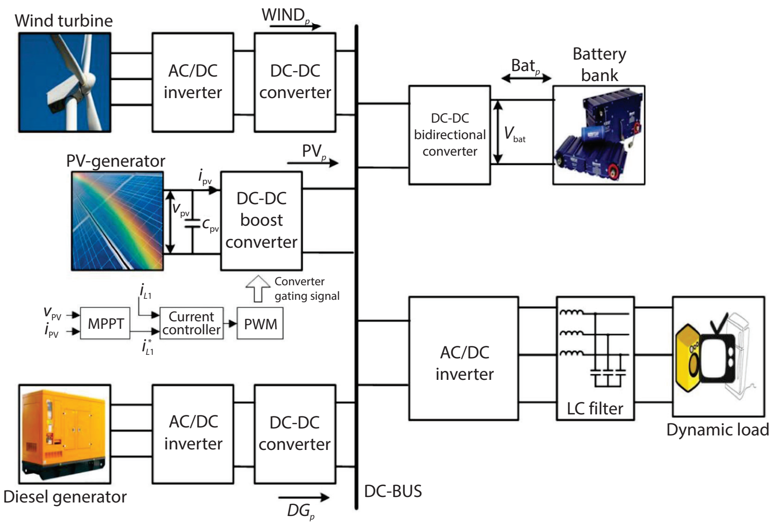


**Figure 1. Output power of the PV battery system**

It can be seen from fig. 1 that the smooth output of PV panel power can be achieved by adjusting the charge and discharge of the battery.

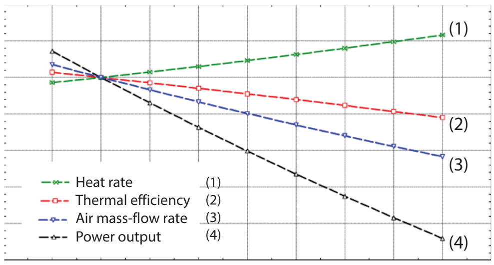


**Figure 2. Electricity and heating efficiency of gas turbine**

## Gas turbine

As the leading power equipment in the entire CCHP system, gas turbines account for about 40% of its cost. As the cost of auxiliary gas turbines decreases significantly with the increase in gas turbines, gas turbines' cost per unit capacity also shows an overall increase in capacity. The power and heating efficiency of a gas turbine is related to its load rate. Figure 2 shows the change curve of the gas turbine mechanism's power and heating efficiency under different load rates.

It can be seen from fig. 2 that the power efficiency is always lower than the heating efficiency [5].

## Systematic design and analysis

Large hotels have stable demand for cooling, heating, and electric loads throughout the year, so CCHP systems with PV battery systems are designed for them. The energy flow diagram of the CCHP with the PV battery system is shown in fig. 3.

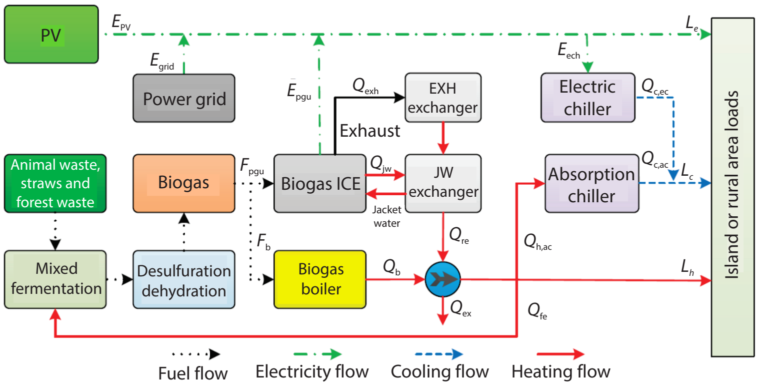


**Figure 3. Energy flow diagram of the CCHP system**

As shown in fig. 3, the electrical load, $E_e$, and the electrical energy, $E_{EV}$, required for charging electric vehicles, the electrical energy, $D$, provided by the large grid, $E_{grid}$, the gas turbine, $E_{pgu}$, and the electrical energy, $E_{PV}$, generated by the PV battery system are satisfied, the cooling load, $Q_c$, is satisfied by the $Q_{ab}$ provided by the absorption chiller. The thermal load, $Q_h$, is satisfied by the $Q_{gs}$ provided by the gas boiler and the $Q_{re}$ provided by the waste heat boiler are satisfied [6].

## System operation mode and strategy analysis

### *Hot follow mode*

The heat follows mode, meaning that the gas turbine's capacity first meets the heat load demand, and the cooling load is entirely supplied by the absorption chiller. In this operating mode, the electric vehicle charging load, $E_{EV}$, is superimposed on the electric load, $E_e$. The energy carried by the high temperature flue gas produced by the gas turbine is recovered by the waste heat boiler and outputs energy, $Q_{re}$, to meet the thermal load, $Q_h$, and cooling load $Q_c$. The electric energy, $Q_{pgu}$, generated by the gas turbine is used to satisfy all-electric loads ($E_{\mathrm{EV}} + E_e$). The shortfall is first supplemented by the electric energy, $E_{\mathrm{PV}}$, generated by the PV battery system. If $E_{\mathrm{PV}}$ cannot be satisfied, it will be supplemented by the grid, $E_{\mathrm{grid}}$.

### *Electric follow mode*

In this operating mode, the electric vehicle charging load, $E_{\mathrm{EV}}$, is superimposed on the electric load, $E_e$, and the gas turbine uses natural gas as fuel. The electric energy, $E_{\mathrm{PV}}$, produced by the PV battery system and the electric energy, $E_{pgu}$, produced by the gas turbine is first used to satisfy all the electric loads $E_{\mathrm{EV}} + E_e$. The high temperature generated by the gas turbine. The energy carried by the flue gas is recovered by the waste heat boiler, $Q_{re}$, which is used to meet the heat load, $Q_h$, and the energy, $Q_{bch}$ required for refrigeration of the absorption chiller. The defective part is provided by the gas boiler as the supplementary part of the system to provide, $Q_{gs}$.

### *Electricity price guidance (Strategy 1)*

– When distributed energy stations are operating off-grid: the CHP generates electricity according to its output limit during peak electricity prices, meeting the energy station's own electricity consumption and part of the electricity load. During low electricity prices, CHP power generation is only used to meet its own electricity consumption. Electricity prices are flat time CHP participates in scheduling.
– When distributed energy stations are connected to the grid: the CHP generates electricity according to its output limit during peak electricity prices to meet the energy station's own electricity consumption and part of the electricity load. During low electricity prices, CHP generation and large grid purchases only meet the energy consumption of the energy station itself.

### *Gas price guidance (Strategy 2)*

– When distributed energy stations are operating off-grid: the CHP power generation during peak gas prices is only used to meet the power consumption of the energy station. The CHP generates power according to its output limit during low gas prices. The CHP participates in dispatch during average gas prices.
– When distributed energy stations are connected to the grid and operate: the CHP generates electricity according to its lower limit of output during peak gas prices and purchases electricity through the large grid to meet the energy consumption of the energy station. During low gas prices, CHP generates electricity according to its output upper limit. Gas prices are standard segment CHP participates in scheduling.

### *Co-ordinated guidance of electricity and gas prices (Strategy 3)*

– When distributed energy stations are operating off-grid: the CHP generates electricity at peak electricity prices and non-peak gas prices at its output limit, meeting the energy station's own electricity consumption and part of the electricity load. Electricity prices are low, and gas prices are not low when CHP generates electricity only used to meet their own electricity consumption. The CHP participates in scheduling during the electricity price flat period.
– When distributed energy stations are connected to the grid: electricity prices are peak, and gas prices are off-peak hours. The CHP generates electricity according to its output limit to meet the energy station's own electricity consumption and part of the electricity load. Elec-

tricity prices are low, and gas prices are not low when CHP is used to generate electricity, and the purchase of electricity by large power grids only meets the power consumption of energy stations. The CHP participates in dispatching during regular electricity price periods.

## Evaluation indicators that take into account the whole life cycle

As a complex energy system, CCHP has various evaluation criteria, but most of the analysis is based on reducing costs and improving the economy. Under the necessary background of my country's current energy shortage and severe smog, to evaluate the social and economic benefits of the CCHP system more scientifically, this paper considers the environmental cost of the system and the life cycle cost of the system.

### *Environmental costs*

The environmental cost, $C_{\mathrm{EN}}$, of the system measures the pollutants generated by power generation with an inevitable standard economic loss, which mainly includes the environmental loss caused by power generation pollutants and the pollution discharge fee paid to relevant departments [7]:

$$C_{\mathrm{EN}} = \sum_{j=1}^{m} (V_{ej} + V_j) Q_j \tag{9}$$

where $m$ is the pollutant category, $V_{ej}$ – the $j$ environmental value of the first pollutant, $V_j$ – the fine for the $j$ pollutant, and $Q_j$ – the discharge amount of the $j$ pollutant.

### *Life cycle cost*

The life cycle cost YCOST refers to the sum of all costs for investment and installation, energy consumption, environmental pollution, operation and maintenance, and recovery after decommissioning for the equipment in the system during its life cycle. In this article, the life cycle cost YCOST includes direct energy purchase cost, $C_{\mathrm{CH}}$, system environmental cost, $C_{\mathrm{EH}}$, operation and maintenance cost, $C_{\mathrm{OM}}$, and investment and installation cost, $C_{\mathrm{DC}}$:

$$Y_{\mathrm{COST}} = C_{\mathrm{CH}} + C_{\mathrm{EN}} + C_{\mathrm{OM}} + C_{\mathrm{DC}} \tag{10}$$

$$C_{\mathrm{CH}} = \sum_{k=1}^{8760} E_{\mathrm{grid}k} C_e + F_{mk} C_f \tag{11}$$

$$C_{\mathrm{EN}} = \sum_{j=1}^{m} (V_{ej} + V_j) Q_j \tag{12}$$

$$C_{\mathrm{OM}} = \sum_{k=1}^{8760} \sum_{i=1}^{N} C_{omi} P_{ik} \tag{13}$$

$$C_{\mathrm{DC}} = \sum_{i=1}^{N} \frac{r(1+r)^n}{(1+r)^n - 1} \mathrm{InCost}_i \tag{14}$$

where $C_e$, $C_f$ are the electricity price and natural gas price, respectively, $C_c$ – the $CO_2$ emission tax, $C_{\mathrm{omi}}$ – the operation and maintenance coefficient of the unit power issued by each output unit, and $P_{ik}$ – the power issued by each output unit in each period.

## Example analysis

### *Example system*

This paper selects a hotel as the research object. The solar panels are installed on the roof, and the solar PV panels are installed on the roof. The roof area is 300 m$^2$. Suppose there are 30 electric vehicles connected to the hotel every day, the capacity of a single battery is 33.8 kWh, and the charging method is disorderly charging. The research period of the thesis is 8760 hours a year. Assuming that the daily electricity price does not change, we compare the system's environmental and economic benefits in the heat following and electricity following modes under different gas turbine capacities. The Monte-Carlo simulation method can simulate the load demand of 8760 hours a year for 30 electric vehicles in the case of disorderly charging [8]. We take 24 hours on a particular day in January of a year as an example and make a load curve, as shown in fig. 4.

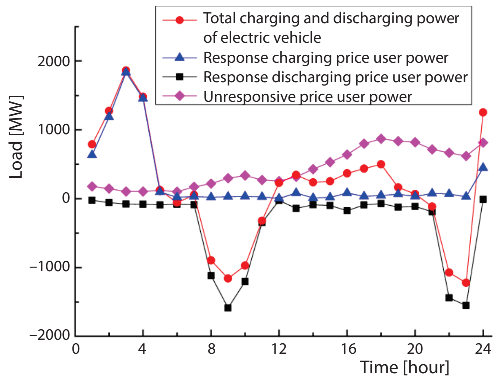


**Figure 4. Charging load curve of electric vehicles**

It can be seen from fig. 4 that the charging load of electric vehicles is relatively large at 18:00-22:00 in the evening, which is in line with the law of general private electric vehicle owners charging electric vehicles after work.

### *Impact of the photovoltaic battery system*

When the gas turbine is selected as 150 kW, the environmental cost and the life cycle cost under the two operation modes of electric follow and heat follow are calculated according to whether it contains a PV battery system or not, as shown in fig. 5.

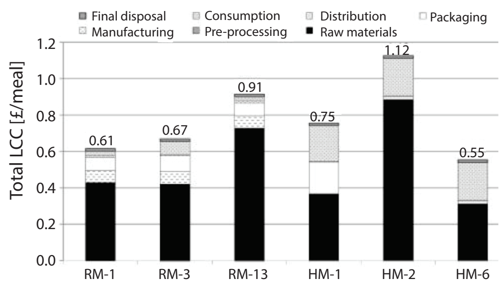


**Figure 5. Comparison of environmental costs and life cycle costs**

It can be seen from fig. 5 that in the two operating modes, the entire CCHP system has better environmental indicators when it includes a PV battery system, and its life cycle cost is better when it does not include a PV battery system. This is because solar energy is completely clean energy and does not incur any environmental costs, so it is more environmentally friendly. Still, its higher installation cost and subsequent operation and management costs will increase the life cycle cost and reduce the overall system economy [9].

### *Comparison of environmental indicators*

The paper chooses environmental cost as the evaluation index. As the gas turbine's rated capacity increases, the environmental cost changes in different modes are shown in fig. 6. This is because in the electric follow mode, the cooling, heating, and electric loads are all provided by gas turbines and gas boilers, and the load demand is all obtained by burning natural gas, which is clean energy, and its pollutant treatment costs and environmental penalty costs are much lower than the grid the cost of burning coal.

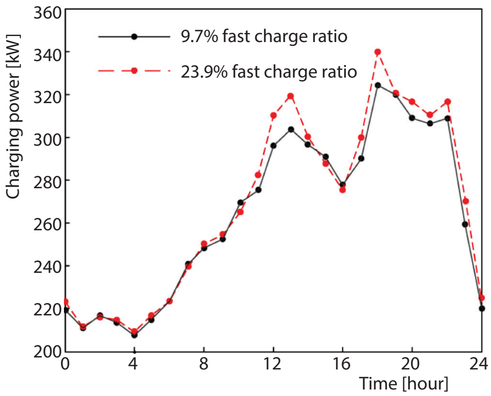


**Figure 6. Environmental indicators**

### *Comparison of life cycle indicators*

The paper chooses the life cycle cost as the evaluation index. With the increase of the gas turbine's rated capacity, the life cycle cost change curve under different modes is shown in fig. 7. It can be seen from fig. 7 that the heat-following mode's life cycle cost is higher than the gas turbine capacity. Hours are lower than the electric follow mode. The amount of natural gas consumed in the heat follow mode increases, while in the electric follow mode, the amount of natural gas consumed is reduced, so the final cost in the thermal follow mode is much greater than that in the electric follow mode [10].

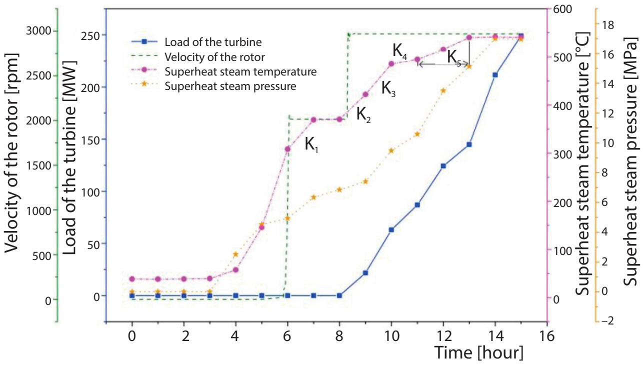


**Figure 7. Life cycle indicators**

## Conclusion

A combined cooling, heating, and power system for electric vehicles with PV battery systems and disorderly charging are established in this paper. At the same time, two operating modes of heat follow, and electric follow are set. Based on the two indicators of environmental cost and life cycle cost, the operating mode is evaluated. Through the analysis of the example system, it is concluded that the PV battery system is more environmentally friendly, but the economy is low. The environmental indicators in the electric follow mode are better. As the gas turbine's rated capacity increases, the heat follows mode's life cycle cost is gradually better than the electric follow mode.

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