An Integrated Energy System Operational Cost Estimation Technique Considering Component Failures

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Abstract. The integrated energy system (IES) is a popular area of research in the energy profession as the energy crisis gets worse and worse. The effect of component failures on the operational expenses of IES has not been taken into account in previous research. As a result, individuals frequently underestimate running expenses, and an overly optimistic operational strategy may result in mishaps like disruptions in the energy supply. In order to assess the normal and failure states of IES, this study suggests a technique of operational cost computation. Moreover, the failure rate and additional running cost are used to calculate the effect of component failures on the IES. The findings show that, in comparison to the conventional calculation technique, the operational cost when component failure is taken into account increases dramatically.

1. Introduction

Traditional forms of energy generation have a large adverse impact on the environment. It is a hot research direction in energy research to maintain the energy supply level and meet the energy demand while minimizing pollution to the environment. Integrated Energy Systems (IES)[1] adjust the operation of each part of the systems so that various forms of energy complement each other. IES helps improve energy efficiency. It can also help promote renewable energy usage, thereby reducing the use of traditional fossil energy sources. As an important indicator for evaluating IES, the economic index requires IES to meet energy supply needs and environmental protection standards while minimizing operating costs and maximizing economic benefits. Therefore, a cost analysis can inform the planning and operation of IES.

A large number of scholars have already studied the operating costs of IES. The reference[2] introduces demand response and cost of carbon into the scheduling strategy to optimize CO_2 emissions and system costs. An IES model including PV, cogeneration, and battery storage was developed to maximize the utilization of PV. Optimization reduces battery life loss and lowers operating costs[3]. In order to reduce system costs and improve energy efficiency, an optimal operating model that considers the energy price response is proposed[4]. A day-ahead dispatching strategy that includes electricity-to- gas components considering demand response is proposed[5]. It is experimentally confirmed that the dispatching strategy can shift load, increase income, promote renewable energy consumption, and improve energy utilization.

However, when a component fails, the energy dispatching scheme will change to meet the energy demand, and it will cause an increase in operating costs and harm economic interests. Along with the prolonged operation of IES, each component's loss and failure rate rise. The stability of the IES operation will be affected. In summary, assessing the impact of component failure on operating costs is a necessary task. However, few studies focus on the component failures in operation cost, leading to underestimating operating costs and over-optimistic operations.

This paper considers the impact of component failure on operating costs in calculating IES's operating costs. The failure impact factor is calculated based on the incremental operating costs and failure rates for various component failure conditions. The case study analyzes the effect of component failure on the cost of system operation and verifies the effectiveness of the proposed method.

2. Integrated Energy Systems Model

IES consists of three segments: supply, conversion and transmission of energy[6]. The energy supply segment includes wind turbines (WT), grids, and photovoltaics (PV). The energy conversion segment contains energy conversion components such as the combined heat and power units (CHP). The energy transmission segment consists of district power systems, district heating systems, and district cooling systems.

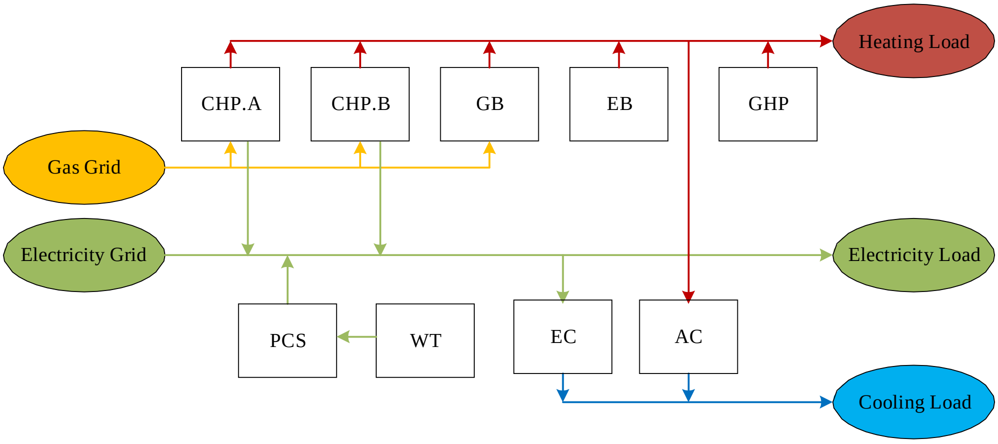


Figure 1. A typical integrated energy system.

Figure 1 shows the topology of a typical IES. It contains the combined heat and power unit (CHP)[7], gas boiler (GB), electric boiler (EB), ground source heat pump (GHP)[8], absorption chiller (AC), electric chiller (EC), photovoltaic (PV) and wind turbine (WT)[9]. The component constraints are shown as follows,

$$H_{CHP} \square \square_{CHP} P_{CHP}$$

$$P_{CHP} = \square \mathrm{CHP}\, G_{CHP}\, H_{GB} = \square\; G_{GB}\, H_{EB} \square \square\; P_{EB}$$

$$H_{GHP} \square_{GB} \square_{GHP} P_{GHP}\, O_{EC} = \square\; EC\, P_{EC}\, O_{AC} = \square\; AC$$

$$_{EB} \qquad H_{AC}$$

(1)

(2)

(3)

(4)

(5)

(6)

(7)

$$\begin{cases} P_{Wt} = \dfrac{V - V_{in}}{V_r - V_{in}} P_r & V_{in} \le V \le V_r \\ P_{Wt} = P_r & V_r \le V \le V_{out} \\ 0 & V \le V_{in},\ V \ge V_{out} \end{cases} \quad (8)$$

In the equations, H, P, G, and O indicate heating, electricity, gas, and refrigeration, respectively; subscripts indicate components; η indicates the component efficiency; λ_{CHP} indicates the thermoelectric conversion efficiency of CHP; P_r indicates the capacity of WT; V_{in}, V, $V_{r,}$ and V_{out} indicate the cut-in wind speed, real-time wind speed, rated wind speed. and cut-out wind speed, respectively.

3. Proposed Operating Cost Calculation Method Considering Component Failures

Operational Optimization Model

The operational goal of IES is to enhance the economy while meeting electricity, heating, and coolingneeds. The objective function of the operational optimization model is,

$$C \square C_{Ele} \square C_{Gas} \square C_{Main}$$

(9)

Where C_{Ele}, C_{Gas}, and C_{Main} are the cost of electricity, gas, and maintenance purchased by IES, respectively.

The energy balance constraints include balances of electricity, heating, and cooling, which ensure areliable load supply,

$$P_{Gird} + P_{CHP} + \square P_{PV} + P_{WT} \square\square\square_{CS} = L_E + P_{EC} + P_{GHP} \square P_{EB}$$

$$H_{CHP} + H_{GHP} + H_{EB} + H_{GB} = L_H + H_{AC}$$

$$O_{EC} + O_{AC} = L_C$$

(10)

(11)

(12)

Where η_{cs} indicates the converter efficiency; L_E, L_H, and L_C are the electricity load, heating load, andcooling load, respectively; P_{Grid} indicates the purchasing power from grids.

Operating Cost Calculation Method Considering Component Failures

The process of operation cost calculation considering component failures is shown in Figure 2.

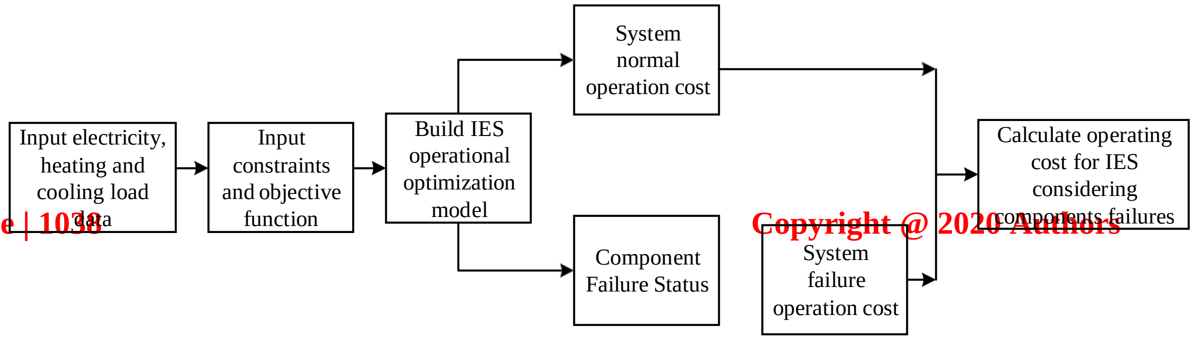


Figure 2. The flowchart of operating cost calculation considering component failures.

The optimal scheduling scheme can be obtained by solving the operational optimization model. Then, the operating costs of the normal system state and failure states can be calculated respectively. The operating cost of the IES considering component failure is related to the failure rate of components, as shown in Equation (13).

$$\begin{cases} C = P_R \cdot C_R + \sum_{i=1}^{n} P_i \cdot C_i \\ \sum_{i=1}^{n} P_i = 1 \end{cases} \tag{13}$$

where P_R indicates the probability of normal system operation; C_R indicates the cost of normal system operation; n indicates the number of failed states; P_i indicates the probability of failure states; C_i indicates the operating cost of failure states i.

Different components have different failure rates, and the operating costs of IES vary between the different component failures. A failure impact factor is introduced to analyze the impact of different components on the operation cost. It can be calculated as follows,

$$\Delta C = \left(C_i - C_R \right) \cdot P_i \tag{14}$$

The failure impact factor is related to the component failure rate and the incremental cost of a component failure. Selecting components with relatively small failure impact factors can help improvethe economy of the IES.

4. Case Studies

The proposed operating cost calculation method is tested in IES, as shown in Figure1. Table 1 shows the parameters of the components. The system operation time is one year, including four typical seasons(spring, summer, autumn, and winter). The electricity price for peak hours (11:00-15:00 and 19:00- 21:00), valley hours (0:00-7:00), and flat hours (8;00-10:00, 16:00-18:00, and 22:00-23:00) are 1.32 yuan/kWh, 0.38 yuan/kWh and 0.84 yuan/kWh, respectively. The failure states in the IES include the failures of GHP, GB, AC, EC, Power Conversion System (PCS), WT, single CHP, and double CHPs.

Table 1. Component parameters.

	Capacity (kW)	Efficiency	Failure rate (occ./year)
EB	200,000	0.9	0.0456
GHP	8,000	5	0.0741
GB	500,000	0.95	0.0855
EC	200,000	3	0.0103
AC	750,000	0.8	0.0684
PCS	55,000	1	0.0684
WT	55,000	-	0.0684
CHP	100,000	0.55	0.0684

Results of Operating Costs Considering Component Failures

The operating costs for the different component failures are shown in Figure 3. Since the efficiency of EB is lower than that of GHP, the output of EB is zero at the normal state. Therefore, EB failure has no impact on the operating costs of the IES. The failure impact factor of components is shown in Table 2.

Table 2. Failure impact factor

	EB	GHP	GB	EC	AC	PCS	WT	Single CHP	Double CHP
ΔC	0	26,57	25,93	21,843	116,852	61,778	61,778	110,801	197

5 2

It shows that AC failure and single CHP failure have large impacts on the system operating cost. Failure of these two components leads to significant power supply shortages. The system purchases much more power from the grid to satisfy energy demands, significantly increasing overall operating costs. The failure impact factors of EC and double CHP are small because the corresponding component failure rates are low.

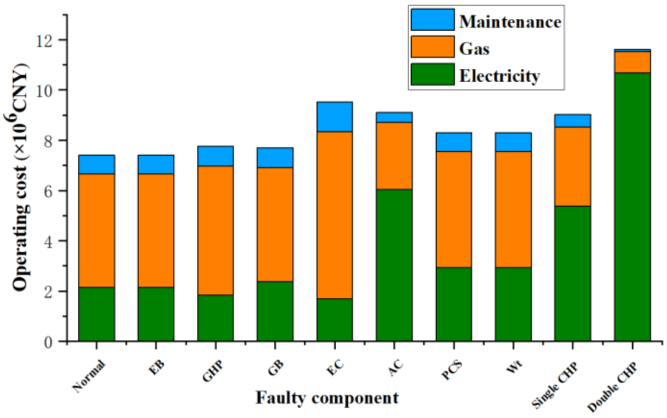
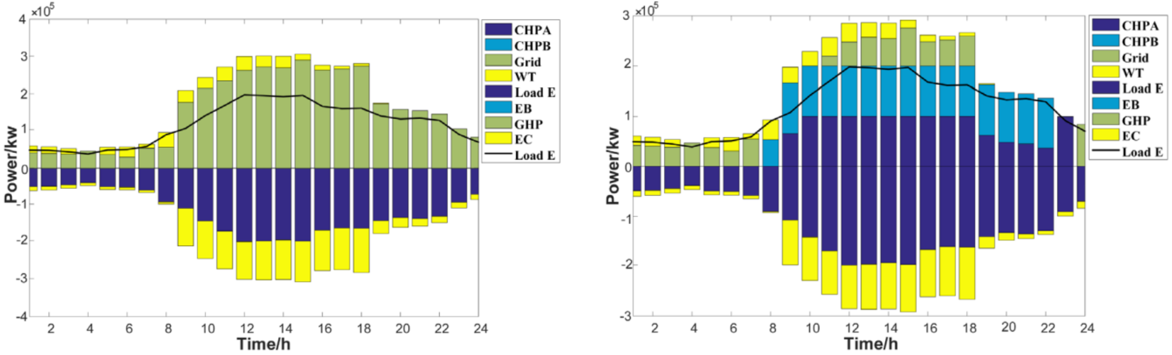


Figure 3. System operating costs of failure states.

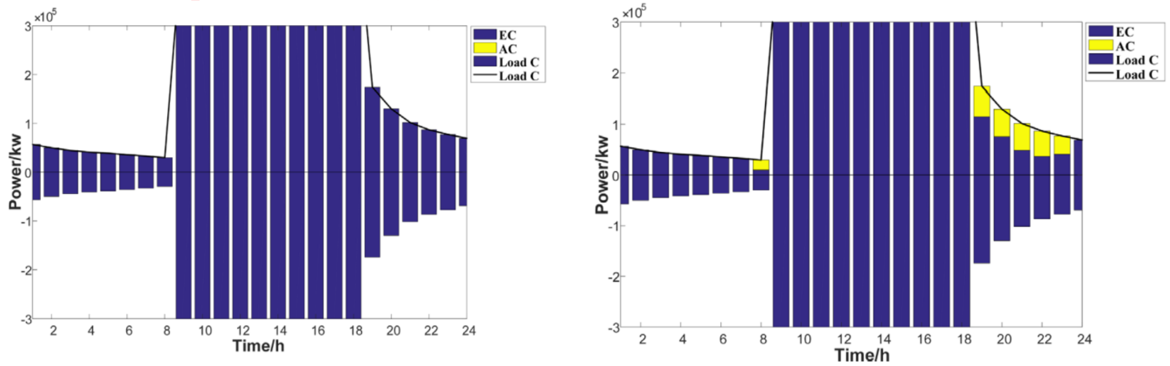
As shown in Figure 3, the operating cost of the IES considering component failure is 7.4034 × 10^6 yuan, while the operating cost of a normal state is 7.3992 × 10^6 yuan. The operating cost increases by 465,756 yuan when component failures are considered. As the components operate for a long time, they will become worn and aging, increasing the failure rate. It will also cause a significant increase in operating costs considering component failures, which will hurt the system's economy.

Impact of Component Failure

Absorption Chiller Failure



(a) Electricity dispatch strategy (AC failure) (b) Electricity dispatch strategy (normal state)



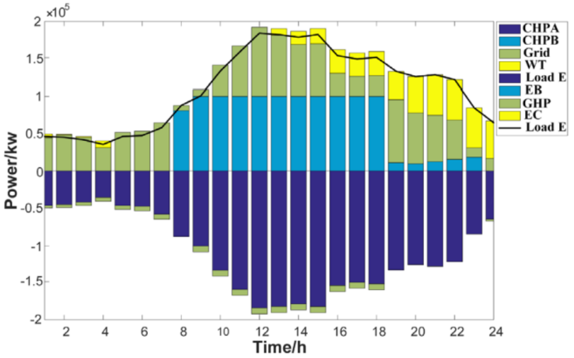
(c) Cooling dispatch strategy (AC failure) (d) Cooling dispatch strategy (normal state)

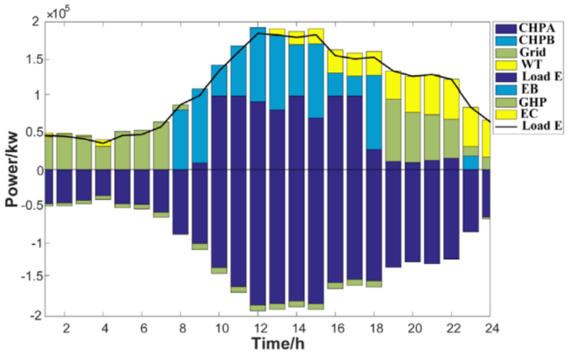
Figure 4. Dispatch strategies for electricity and cooling in summer.

As shown in Figure 4, the EC bears the entire cold load when the AC fails. The AC no longer absorbsheat and has no heat load in the summer, so the CHP unit stops running. The system purchases more power from the grid to compensate for insufficient power supply due to the outage of CHP. EC's increased output leads to an increase in electricity consumption, further boosting the power purchased by the system grid.

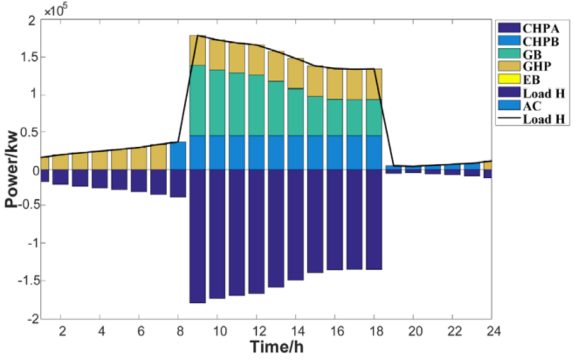
Due to the shutdown of the CHP unit, system natural gas consumption is reduced. Although the outages of AC and CHP result in lower system maintenance costs, a large increase in the electricity demand during the peak period causes a significant increase in power purchase costs. In summary, the overall operating cost of IES increases significantly.

Single CHP Unit Failure



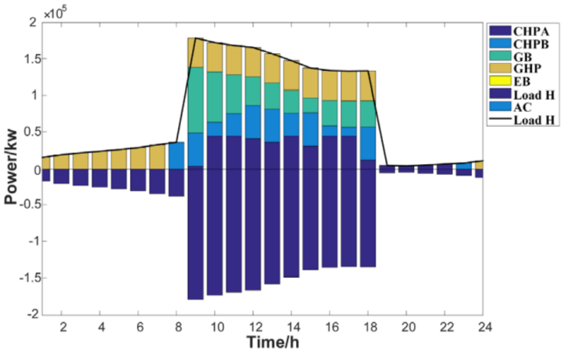


(a) Electricity dispatch strategy(Single CHP failure)



(c) Heating dispatch strategy(Single CHP failure)

(b) Electricity dispatch strategy (normal state)



(d) Heating dispatch strategy (normal state)

Figure 5. Spring electricity and heating dispatching diagram.

As shown in Fig 5, when one CHP unit fails, the other CHP unit operates at the maximum output. Since it still cannot meet the demand, the electricity purchased from the grid increases significantly. GB's heat output increases because the CHP unit's failure results in an insufficient heat supply.

When a single CHP unit fails, system gas consumption and the purchased gas cost reduce. Maintenance costs decrease with the shutdown of CHP. The system significantly increases its power purchases from the grid at higher prices to meet electricity demands, resulting in a significant increase in purchased power costs. In summary, the system operating costs also increased significantly.

5. Conclusion

This paper proposes an operating costs calculation method for IES considering components failures. We consider both impact and failure rates when calculating the system operating cost. It is verified that the system operating cost is significantly higher after we consider the failure rate. This approach can provide an economic reference, which can avoid underestimating the operating costs of IES. Based on the failure impact factor, the impact of each component failure on the operating costs can be evaluated. Therefore, the enhanced inspection and maintenance of critical components will help enhance the stability of the system and improve economic efficiency.

Acknowledgments

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