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Optimal scheduling of regional integrated energy system considering multiple uncertainties

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Abstract. Integrated energy system (IES) is an effective way to realize the efficient utilization of energy. Under the deregulated electricity market, IES operator gains profits by providing customers with energy service, including electricity, heat or cooling energy. With the deepening of market reform, higher penetration rate of renewable energy, economic risks embed in the IES. Based on this, an optimal scheduling model of regional IES considering uncertainties is proposed, aiming at maximizing the profits. Scenario analysis method has been adopted to model the uncertainties: Markov-Chain-Monte-Carlo (MCMC) sampling method, which has a better performance in fitting the probability distribution, is utilized to generate scenarios; K-means clustering method is applied to narrow down the sampling sets. By replacing the parameters in the deterministic model with the sampling sets, a series of optimal results can be achieved. The case study shows that the cooling storage tank can improve the economic benefits about 4.97% by converting electricity to cooling energy at lower price period and releasing energy at peak hours. Besides, through the proposed optimization model, operators can have a straight understanding of the venture brought by the uncertainties and a more reliable scheduling result is formed for reference.

1 Introduction

Energy development used to rely on the utilization of traditional fossil energy, causing many problems such as resource wasting and environment pollution[1-2]. Building an effective IES is one of the most important measures to solve the problems.

Experts have done a lot of research on the optimization of IES. In Ref [3] an IES optimal scheduling model with electricity as the core is established, aiming at minimizing the cost and optimizing environmental conservation. In Ref [4] a RIES (Regional IES) model is established, including many energy conversion equipment and storage equipment. Energy storage equipment is an important component in RIES, such as storage battery, cooling storage tank and heat storage tank5. Good scheduling is crucial to the sustainable development of the system. Most of the papers have analysed the effect of the storage battery on peak shifting, but cooling/heat storage tank is less mentioned.

Meanwhile, there are many uncertain factors existing in the system, for example, the time-variant price in deregulated electricity market, the fluctuating wind power and energy demand. These are neglectable for a precise optimization model. In uncertainty analysis, the probability-based simulation method is commonly used[6-9]. In Ref 7, Bornapour. M elaborates on Monte Carlo sampling, and scenarios reduction. Subsequently, MCMC is proposed which is widely used in the risk evaluation of power system[8-9].

Based on the researches, from the perspective of the IES operator, this paper proposes an optimal scheduling method considering uncertainties of electricity price, wind power and electricity demand, aiming at maximizing the profits. The main contribution is as follows:

- A deterministic optimal scheduling model of RIES has been first established, involving electricity, wind power and cooling energy, equipped with water-cooling system and EV charging piles. The significant economic benefit of water-cooling system has been discussed in case study.
- In order to achieve a more precise scheduling method considering of uncertainties, the probability-based simulation method is adopted. MCMC is used to generate scenarios because of its good performance on fitting the distribution and K-means clustering is used to narrow down the size. The economic risks brought by uncertainties have been analyzed deeply.

2 Main equipment and optimization model of RIES

A typical structure of RIES is shown in Figure 1.

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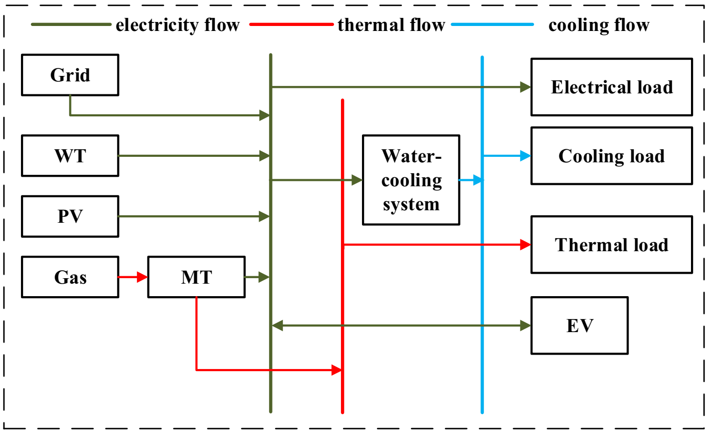

Figure 1. A typical structure of regional integrated energy system

In deregulated electricity market, RIES can connect to the main grid through the Point Common Connection (PCC) and purchase electricity from the main grid. It works as a retailer, selling various kinds of energy to customers nearby by adding a certain tariff. In this paper, we mainly focusing on the supply-demand model of electricity and cooling energy. And the main equipment is the water-cooling system. Water cooling system is usually composed of water-cooling machine, cool-storage tank, inlet/outlet pumps, etc. Their mathematical models are as follows9:

- Water-cooling machine:

$$Q_{WC} = COP_{WC} \cdot P_{WC} \tag{1}$$

where: Q_{WC} is the cooling power of the machine, COP_{WC} is the coefficient of performance, P_{WC} is the electrical power.

- Cool-storage tank:

$$W(t) = (1-\varepsilon)W(t-1) + Q_{s,t}\ \eta_s - Q_{r,t} / \eta_r$$

where: $W(t)$ equals to the remaining cooling energy at time t, Q_s is the storage rate, Q_r is the releasing rate, ε represents self-loss , η_s / η_r is the storage/releasing efficiency.

During the storage process, inlet pump and cooling machine work together to produce cooling energy:

$$P_s = P_{in}^P + P_{WC} \tag{2}$$

While during the releasing process, only the outlet pump works to provide RIES with cooling energy:

$$P_r = P_{out}^P \tag{3}$$

where: P_{in}^P and P_{out}^P represent the power of pumps, P_s and P_r represent the electrical power to store or release cooling energy.

These two processes can be turned on/off independently with the control of in/out pumps.

2.1 Objective function

In this business model, RIES sells energy to users by adding a certain tariff on its cost. Therefore, the optimization objective can be converted to minimizing the total cost of the system in a day. The objective function is as follows:

$$\min \sum_{t=1}^{T=24} c_{e,t} P_{grid,t} + c_{ev,dis} P_{ev,dis} - c_{ev,ch} P_{ev,ch} \tag{4}$$

The first item represents the cost of buying energy from the main grid, $c_{e,t}$ is the electricity price at time t; the second item represents the cost of RIES buying energy from EV. $P_{ev,dis}$ is the discharge power. $c_{ev,dis}$ is the price of EV discharging process; the last item represents the earning from providing EV with charging service. $c_{ev,ch}$ represent the additional price of EV charging service and $P_{ev,ch}$ is the charge power; the total period is 24 hours, $\Delta t = 1$ is omitted.

2.2 Electrical and cooling power supply-demand balance

To ensure the security of the power system, the electrical demand balance must be satisfied:

$$P_{grid,t} + P_{WT,t} + P_{ev,dis,t} - P_{ev,ch,t} - P_{in,t} - P_{out,t} = P_{demand,t} \tag{5}$$

where: $P_{WT,t}$ is the power of WT; $P_{demand,t}$ is the electrical demand at time t.

The cooling power can be greater than the cooling demand $Q_{demand,t}$:

$$Q_{r,t} \geq Q_{\text{demand},t} \tag{6}$$

2.3 Other constraints

$$Q_{min} \leq Q(t) \leq Q_{max} \tag{7}$$

$$Q(T) = Q(0) \tag{8}$$

For EVs, the sum of $N_{ev,ch}$ and $N_{ev,dis}$ (number of charging/discharging EVs) should be fewer than N_{ev}, the predicted amount of EV.

$$N_{ev,ch} + N_{ev,dis} \leq N_{ev} \tag{9}$$

3 Method of uncertainty analysis

To deal with the uncertainties of the price and power in the above model, MCMC sampling method and K-means clustering are utilized10. Then, we can substitute the original data set with those sampling sets in order to figure out the distribution characteristic of cost.

3.1 MCMC sampling

The common Monte-Carlo sampling requires for a huge number of random samples, then MCMC algorithm is proposed.

The detailed process is as follows8:

a) Set the objective stationary distribution $\pi(X)$;

b) Randomly initialize $x_0 \in X$;

c) For $i = 1 : N_s$:

i. Obtain x^* according to the transition probability of Q, satisfying that $Q(x_i, x^*) = q(x^* \mid x_i)$;

ii. Generate a random number u in the range of [0,1];

iii. If $u < \alpha(x_i, x^*) = \pi(x^*)Q(x^*, x_i)$, then x^* is accepted, $x_i \rightarrow x^*$; else, the state remains.

where: N_s is the sampling time, while it is not the actual sample number, because some of sampling results are declined. The acceptance rate can be expressed as:

$$\alpha(i,j) = min\left\{\frac{\pi(j)Q(j,i)}{\pi(i)Q(i,j)}, 1\right\} \quad (10)$$

3.2 Scenario reduction - K-means clustering

Suppose that all samples are divided into K clusters $(C_1, C_2, ..., C_k)$. In each cluster, the goal is to minimize the sum of all points' Euclidean distances to the centroid of the cluster11. To put it in another way:

$$\min E = \sum_{i=1}^{k} \sum_{x \in C_i} \| x - \mu_i \|_2 \quad (11)$$

where: μ_i is the centroid of cluster i.

4 Case studies

4.1Basic architecture of the system

The case is based on an energy station in Nanjing, equipped with a set of WT, a set of water-cooling system, 8 charging piles. The station needs to provide both electrical and cooling power for the commercial customers nearby. The detailed parameters of device involved are listed in Table 1. TOU electricity price is listed in Table 2.

Table 1. Parameters of device

Charging pile	$\overline{P}_{ev,ch} / \overline{P}_{ev,dis}$	$c_{ev,ch}$	$c_{ev,dis}$
	120/80kw	0.71 RMB/kwh	1.5 RMB/kwh
Water cooling system	$\overline{P}_s / \overline{P}_r$	Q_{max} / Q_{min}	
	8000/ 8000kw	25000/ 10000kwh	

Table 2. TOU electricity price

Period	Price（RMB/kwh）
8:00~12:00 17:00~21:00	1.0697
12:00~17:00 21:00~24:00	0.6418
0:00~7:00	0.3139

4.2 Optimal scheduling results of RIES in basic situation

The optimal scheduling results are shown in Figure 2. It can be seen that most of the power purchased from main gird is used for cooling system to supply the cooling demand. The system satisfies both electrical and cooling demand at a cost of 157212 RMB.

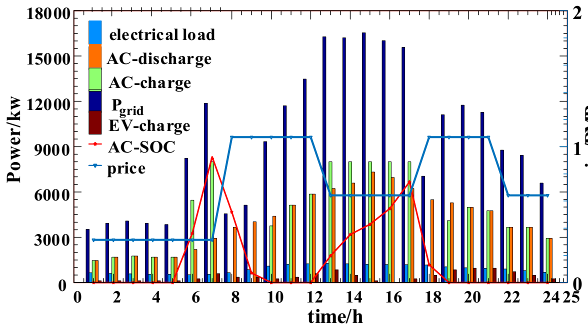

Figure 2. Optimal results of the energy station RIES

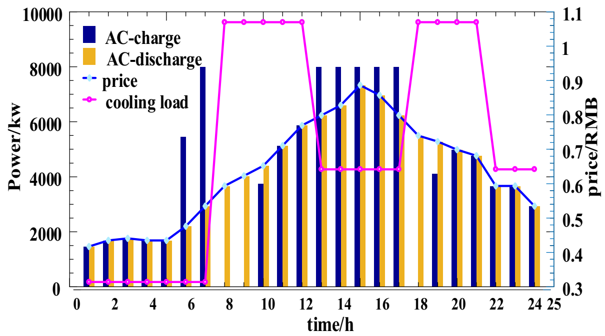

Figure 3. Working state of cooling system

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Next, we focus on analysing the working state of water-cooling system, which plays an important role in cutting down the cost of the system operation. As shown in Figure 3, At 6~7am, storage rate is much greater than releasing rate, and that increases the cooling energy stored in the tank. When in the peak period like 8am to 12am, first the out pump works alone to release cooling energy at the least cost. While due to the limited capacity of tank, from 10am to 12am, the water-cooling machine works again. Then from 1pm to 5pm, with a lower price, the cooling system continues to work, in order to reduce the operation cost in the next peak period. At the same time, the water storage tank also releases energy to supply the cooling load.

When there is no water storage tank, the total cost is 164985 RMB. It is obvious that with the adoption of water storage tank, the economic benefit can be improved a lot, approximately 4.94%.

4.3 Optimal scheduling results with consideration of multiple uncertainties

In this part, three uncertain variables are selected, including electrical load, wind power and electricity price. Suppose the deviation of wind power and the electrical load correspond to normal distribution. Set the standard deviation of WT as 20% of the predicted value and set standard deviation of electrical load as 10%. Besides, the electricity price is evenly distributed within the range of ±10% of the TOU price.

Through the proposed MCMC scenario generating and reduction process, 500 sets of data has been obtained which are substituted into the optimal scheduling model to calculate the total operation cost of the day. The Cumulative Distribution Function (CDF) and probability density function (pdf) of the cost are presented in Figure 4.

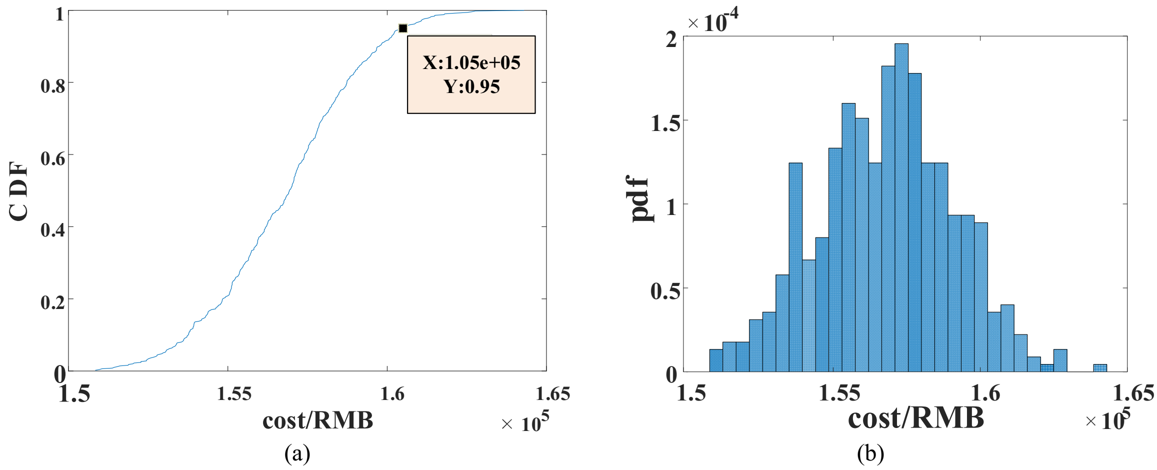

Figure 4. CDF and pdf of the operating cost

At a certain degree of confidence (β = 0.95) as marked in Figure 4(a), the maximum cost that may occur is 160497 RMB, about 2.1% greater than the cost without consideration of uncertainties. And according to Figure 4(b), the distribution of operation cost is close to normal distribution, with an estimate standard deviation 1.47% of the mean cost. In this case, compared with the pre-set range of those variables (10% and 15%), the fluctuation range of the cost is insignificant. That means the stability of the system is good with the regard of these three variables, and operators of the station needs to bear little economic risks. That is mainly because in this model, electrical load takes only a small part in total energy demand and WT's output may have a little influence on the operation because of the limited capacity.

5 Conclusion

The integrated energy system is an important way to achieve multi-energy complementary, coordinated and efficient development. This paper focuses on the role of water-cooling system and the impact of uncertainties on the economic performance of system operation.

- As illustrated in Section 5, the water-cooling system plays an important role in peak load shifting, not only lightening the transmission pressure for the main grid, but also cutting down the cost of the operator and enhancing the scheduling flexibility of RIES greatly.
- Considering these uncertainties, a more reliable scheduling result is formed for reference. Besides, CDF and pdf of the total cost help to evaluate the economic stability, as well as analyse the economic venture.

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