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Co-optimization of regional integrated energy system and electric vehicle charging strategies: A case study of Hangzhou#

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ABSTRACT

With the transformation of the energy structure and the rising penetration of electric vehicles (EVs), the planning and optimization of regional integrated energy systems (RIES) face new challenges. Using an industrial park in Hangzhou as a case study, this paper first optimizes the traditional high-carbon energy system by introducing electric chillers, ice storage, air source heat pumps, and battery storage, achieving significant reductions of approximately 48% in annual operating costs and 66% in carbon emissions. When EV charging loads are further incorporated into system planning, it is found that the demands for electricity, energy storage, and charging infrastructure increase significantly, resulting in higher total system costs and carbon emissions. To mitigate peak load pressures caused by EV charging, this study compares uncoordinated and coordinated charging strategies. The results show that coordinated charging not only reduces peak load by about 30%, but also decreases the required numbers of charging piles and energy storage capacity by 31% and 18%, respectively, while further lowering steam consumption, system costs, and carbon emissions, thus significantly improving system economy and flexibility. The findings suggest that fully tapping into the flexibility of EV loads and implementing smart coordinated charging are key to achieving low-carbon and efficient operation of RIES in future industrial parks.

Keywords: Regional integrated energy system, electric vehicle, charging strategy, capacity planning

NONMENCLATURE

Abbreviations	
AC	Absorption Chiller
ASHP	Air Source Heat Pump
CES	Cold Energy Storage
CP	Charging Point
EV	Electric Vehicle
EC	Electric Chiller
EES	Electrical Energy Storage
HX	Heat Exchanger
MILP	Mixed-integer Linear Programming
RIES	Regional Integrated Energy System

1. INTRODUCTION

In recent years, the integration of renewable energy and multiple energy sources has promoted the development of regional integrated energy systems (RIES) toward multi-energy complementarity and diversification[1, 2]. During this process, the inclusion of flexible loads such as electric vehicles (EVs) presents new challenges for energy planning[3]. This study focuses on a biopharmaceutical industrial park in Hangzhou, China, where the buildings require cooling throughout the year and heating during winter. The original energy system in this park mainly relies on absorption chillers (ACs) and heat exchangers (HXs), resulting in high operating costs and significant carbon emissions. To address these issues[4, 5], this study proposes the introduction of electric chillers (ECs) and cold energy storage (CES) on the cooling side, the combination of air source heat pumps (ASHPs) and heat exchangers (HXs) on the heating side, and the addition of electrical energy storage (EES) to reduce both operating costs and carbon emissions.

In addition, with the increasing adoption of EVs, their charging demand as a new flexible load must also be considered. Therefore, based on the existing optimization model, this paper designs and analyzes both uncoordinated and coordinated charging strategies. Monte Carlo simulations are used to generate EV charging load curves, and the impacts of different charging strategies on the configuration and operation of the integrated energy station are evaluated. The structure of this paper is as follows: Section 2 introduces the system composition and optimization model of the

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Hangzhou RIES and presents the optimization results without considering EV charging loads; Section 3 incorporates EV charging loads, describes the simulation of charging loads, and compares system planning under uncoordinated and coordinated charging strategies; Section 4 provides the conclusions.

2. REQUIREMENTS OF PAPER STRUCTURE

The study area in this paper is a development zone in Hangzhou, where most buildings are used for biopharmaceutical industries. A regional energy station supplies both cooling and heating to these buildings. Cooling demand exists throughout the year, while heating demand is mainly concentrated in winter. The current structure of the RIES is shown in Figure 1. Steam is the main energy source. The system is equipped with ACs and HXs. ACs, driven by steam, provide year-round cooling, while HXs supply comfort heating during the winter.

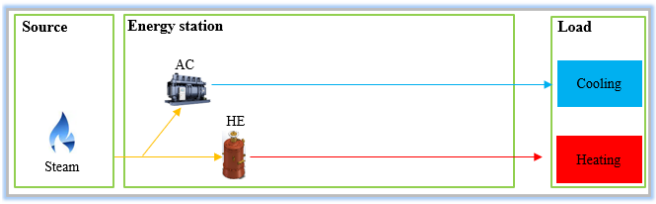


Fig. 1 Original energy system structure

However, this traditional system has clear disadvantages. The overall efficiency of the ACs and HXs is low, and the energy output depends on high-temperature steam. In addition, the system does not have energy storage facilities or flexible regulation capabilities, making it difficult to take advantage of time-of-use electricity pricing. As a result, the system shows high energy consumption, energy costs, and carbon emissions.

2.1 Optimization Methods

To address the high cost and carbon emissions of the original system, this study develops a mixed-integer linear programming (MILP) model with the objective of economic optimization[6, 7]. The model is built on the MATLAB platform using YALMIP for modeling and solved with the Gurobi optimizer. To ensure comparability of results, all calculations use an hourly time step over an annual optimization period.

Input data: 1. Cooling and heating load profiles for three representative days in summer, winter, and transition seasons (based on actual data); 2. Steam price (0.305 RMB/kWh); 3. Time-of-use electricity prices for 10kV industrial users in Hangzhou across 12 months (used by the optimization model to schedule equipment operation and energy storage charging/discharging); 4. Parameters of each device.

Output data: 1. Equipment selection results; 2. Investment cost of system equipment; 3. System operating cost.

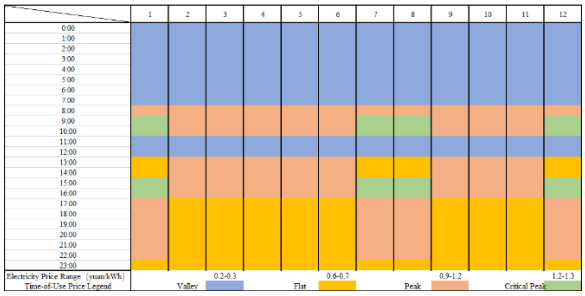
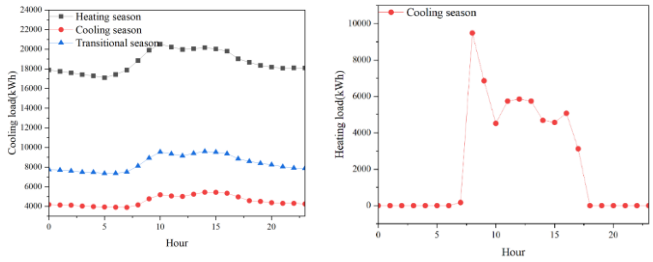


Fig. 2 Time-of-Use Electricity Price



A. Cold load *B. Hot load*

Fig. 3 Typical day load curve

Table.1 Equipment Performance Parameters

Equipment	Performance Parameter	Value
EC	Price (RMB/kW)	1100
	COP	4
AC	Price (RMB/kW)	1200
	COP	1
ASHP	Price (RMB/kW)	1100
	COP	4
HX	Price (RMB/kW)	440
	COP	1
EES	Price (RMB/kW)	1000
	Charging Efficiency	0.95
	Discharging Efficiency	0.95
	Lower Bound of Depth of Charge/Discharge	0
	Upper Bound of Depth of Charge/Discharge	0.4
	Lower Bound of State of Charge	0
	Upper Bound of State of Charge	1
CES	Price (RMB/kW)	100
	Charging Efficiency	0.95
	Discharging Efficiency	0.95
	Lower Bound of Depth of Charge/Discharge	0
	Upper Bound of Depth of Charge/Discharge	0.2
	Lower Bound of State of Charge	0
	Upper Bound of State of Charge	1
CP	Price (RMB)	5000
	Power (kW)	7
Ice maker Unit	Price (RMB/kW)	1500
	COP	4

The model constraints are set as follows:

The objective function of the model aims to minimize the sum of the annualized investment cost of equipment and the operating cost, while meeting the energy supply demand. In the simulation, the loan interest rate is assumed to be 8% with a repayment period of 10 years.

$$minObj = Obj_{inv} + Obj_{operation} \quad (1)$$

Where Obj represents the objective function, which is defined as the sum of the annualized investment cost and the annual operating cost of the energy system (in RMB). Obj_{inv} denotes the annualized investment cost (in RMB), and $Obj_{operation}$ denotes the annual operating cost (in RMB).

Power balance constraint:

$$P_{grid}^{t} + P_{EES}^{dis,t} = P_{ASHP}^{t} + P_{EES}^{ch,t} + P_{CES}^{ch,t} + P_{EC}^{t} + P_{EV}^{t} \quad (2)$$

Where P_{grid}^{t} represents the grid power at time t (kW); $P_{EES}^{dis,t}$ denotes the EES discharging power at time t (kW); P_{ASHP}^{t} denotes the ASHP power at time t (kW); $P_{EES}^{ch,t}$ represents the EES charging power at time t (kW); $P_{CES}^{ch,t}$ denotes the CES charging power at time t (kW); and P_{EC}^{t} represents the EC power at time t (kW).

Cold load balance constraint:

$$P_{EC}^{t} + P_{CES}^{dis,t} + P_{AC}^{t} = L_{C}^{t} \quad (3)$$

Where P_{EC}^{t} represents the EC power at time t (kW); $P_{CES}^{dis,t}$ denotes the CES discharging power at time t (kW); and P_{AC}^{t} represents the AC power at time t (kW).

Hot load balance constraint:

$$P_{ASHP}^{t} + P_{HX}^{t} = L_{H}^{t} \quad (4)$$

Where P_{ASHP}^{t} represents the ASHP power at time t (kW); P_{HX}^{t} denotes the HX power at time t (kW); and L_{H}^{t} represents the heating load at time t (kW).

Steam load balance constraint:

$$P_{AC}^{t} + P_{HX}^{t} = P_{steam}^{t} \quad (5)$$

Where P_{steam}^{t} represents the steam load at time t (kW).

Equipment output constraints:

$$0 \le P_{x}^{t} \le C_{x,max} \ \forall x \in \{EC, ASHP, HX, EV, AC\} \quad (6)$$

Where P_{x}^{t} represents the power output of equipment xx at time t (kW), and $C_{x,max}$ denotes the rated capacity of equipment *x* (kW).

Energy storage constraints:

$$\begin{aligned} S(t) &= S(t-1) + \frac{\delta[P_{dis}(t) - P_{ch}(t)]\Delta t}{E(t)} \times 100\% \\ E_{min} &\le E(t) \le E_{max} \\ 0 &\le P_{ch}(t) \le P_{ch}^{max} u_{ch} \\ 0 &\le P_{dis}(t) \le P_{dis}^{max} u_{dis} \\ u_{dis} &\times u_{ch} = 1 \end{aligned} \quad (7)$$

where S(t) and S(t−1) represent the state of charge (SOC) of the energy storage device at time t and t-1 (%); δ denotes the energy conversion efficiency of the storage device (%); $P_{ch}(t)$ and $P_{dis}(t)$ are the charging and discharging power of the storage device at time t (kW), respectively; E(t) is the remaining energy of the storage device at time t (kWh); E_{max} and E_{min} are the upper and lower bounds of the storage device's remaining energy (kWh); P_{ch}^{max} and P_{dis}^{max} are the upper and lower limits of charging and discharging power (kW), respectively. The device is not allowed to charge and discharge simultaneously, and u_{ch} and u_{dis} are 0-1 variables indicating the charging and discharging status, with u_{ch} =1 during charging and u_{dis} =1 during discharging.

2.2 Optimization Results

The optimized system structure is illustrated in Figure 4. On the cooling side, traditional ACs are completely replaced by ECs and CESs. ECs operate during regular hours, while the CES makes ice during off-peak electricity periods and releases cooling during peak-price periods. This approach reduces both system costs and peak power demand. For heating, the optimized scheme introduces ASHPs operating in tandem with HXs. ASHPs are prioritized during off-peak hours, while heat exchangers provide heating during peak periods. The addition of a EES system enables charging with low-cost electricity during off-peak times and discharging during peak times, further flattening the load curve and lowering energy costs.

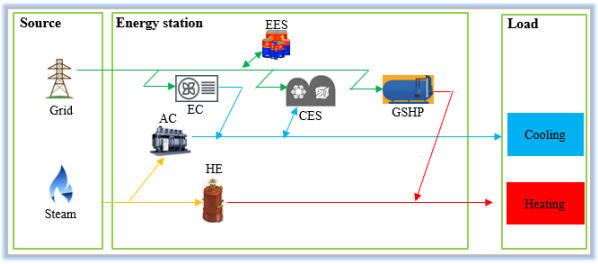


Fig. 4 System structure after optimization

As shown in Table 2, after optimization, the total annual system cost drops from 37.15 million RMB to 19.23 million RMB (a 48% reduction), and annual carbon emissions decrease from 39,807 tons to 13,937 tons (a 66% reduction). Electricity consumption rises to 26,235 MWh, while steam usage drops sharply from 100,525 MWh to 745 MWh, marking a clear shift from steam-based to electricity-based operation.

Table.2 System Configuration Optimization results

Dimension	Initial Configuration	Optimized Result
AC (kW)	34700	0
EC(kW)	0	20800
IES (kW)	0	105600
Ice Maker Unit (kWh)	0	13900
HX (kW)	9500	4400
ASHP(kW)	0	5100
BES (kWh)	0	6600
Steam Consumption (MWh)	100525	745
Electricity Consumption (MWh)	0	26235
Carbon Emissions (tCO_2/year)	39807	13937
Total Cost (10,000 RMB/year)	3715	1923

These results demonstrate that by adding ECs, CESs, ASHPs, and EESs, the RIES can maximize the substitution of steam with electricity and achieve a low-carbon, economical system. The new configuration eliminates high-energy-consuming chillers, uses high-efficiency electric equipment, and takes advantage of price signals and energy storage for cost savings and carbon reduction.

It should be noted that these results are obtained without considering EV charging loads. With the growing adoption of EVs, their charging demand will introduce a new flexible load to the energy system. The following section incorporates EV charging loads and compares uncoordinated and coordinated charging strategies to assess their impact on RIES planning.

3. RIES OPTIMIZATION CONSIDERING EV CHARGING LOADS

Based on the existing optimization model, this section investigates the impact of regional EV charging demand on RIES planning. According to the survey, the working hours in the park are from 8:00 to 18:00 on weekdays. There are 700 identical EVs (private cars) in the park, with their parameters and corresponding values listed in the table.

Table.3 EV Parameters

Parameter	Value
Number of Electric Vehicles	700
Charging Power	7 kW
Battery Capacity	35 kWh
Power Consumption per 100 km	13.4 kWh
Battery Energy Conversion Efficiency	0.95
Desired State of Charge	1

In this study, two charging strategies are further designed to manage charging load: The uncoordinated charging strategy refers to each EV charging immediately upon arrival at a fixed power, without considering load smoothing. The coordinated charging strategy aims to optimize costs by scheduling and shifting charging power, under the premise that the total daily charging demand remains unchanged and user travel is not affected.

3.1 EV charging load generation methods

Based on the above information, the Monte Carlo method is used to generate EV charging loads under the uncoordinated charging scenario[8, 9]. In this strategy, each vehicle begins charging at a fixed power immediately upon arrival. The specific process is as follows: First, the daily driving distance of each EV is randomly generated according to a normal distribution (mean 3.20 km, variance 0.88), and the required charging amount is calculated based on the energy consumption per kilometer. Second, the charging start time for each vehicle is determined using a normal distribution for arrival time (mean 8:00, variance 0.7). The charging duration is then calculated based on the required charging amount and the charging power. Next, the departure time of each vehicle is generated according to a normal distribution (mean 18:00, variance 0.7). Finally, the charging power of all vehicles at each time is aggregated to obtain the daily total EV charging load curve. In total, 12 uncoordinated charging load curves are generated, corresponding to 12 typical days.

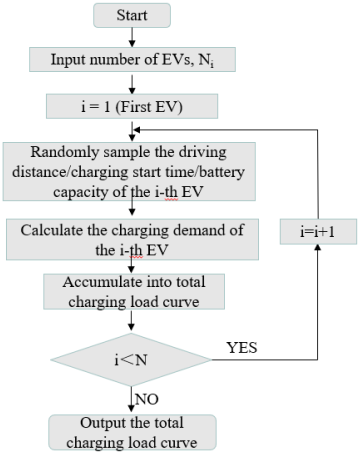


Fig. 5 Uncoordinated charging strategy

The generated EV charging load described above serves as the baseline curve under the uncoordinated charging scenario. Under the coordinated charging strategy, the charging power at each time interval is set as the optimization variable, with constraints on charging power and total charging demand. This is integrated with the RIES optimization model, which aims to minimize the total system cost. The optimal scheduling solution is obtained using the Gurobi solver.

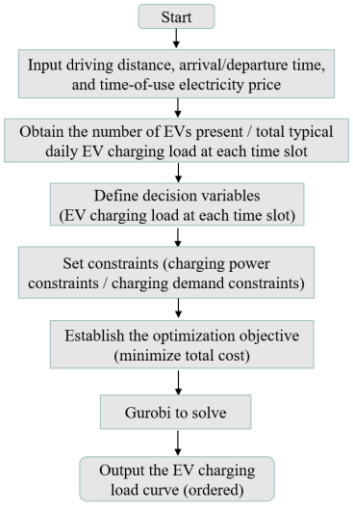


Fig. 6 Coordinated charging strategy

In this section, EV charging loads are introduced based on the previous scheme to further evaluate the impact of EV integration on system planning and to compare the results under uncoordinated and coordinated charging strategies. After simulating the regional EV charging loads, they are incorporated as additional loads into the system optimization model for analysis.

3.2 Optimization Results

Figure 7 shows the system structure with EV penetration. Based on the original system, charging points (CPs) are added to meet the charging demand of EVs.

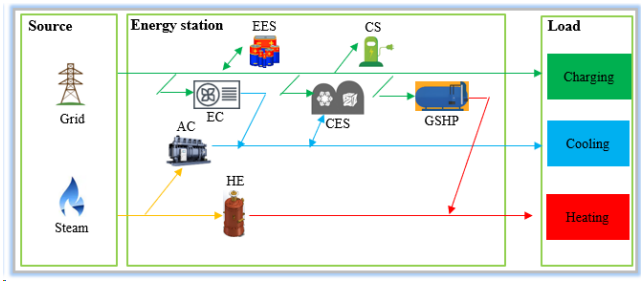
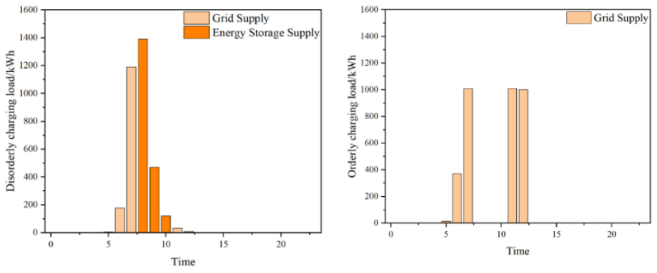


Fig. 7 System structure under EV penetration

Figure 8 presents the EV charging load curves under typical days for both uncoordinated and coordinated charging strategies. The simulation results show that, under uncoordinated charging, there is a significant load peak in the morning, with a maximum value of approximately 1.4 MW. Since this peak coincides with periods of high electricity prices, energy storage is used to supply the load during these times. In contrast, with the coordinated charging strategy, the charging load is distributed more evenly, and the peak is reduced to about 1.0 MW (a reduction of approximately 30%), with the charging process extending into the afternoon, resulting in a much flatter load curve. This reduction in peak load means the RIES relies less on energy storage, and coordinated charging effectively reduces the peak-valley difference on the power supply side, thereby alleviating grid stress.



a. Uncoordinated charging b. Coordinated charging

Fig. 8 EV charging load curve

Table 4 compares the system configurations of RIES under different scenarios. The results show that, after considering EV charging loads, there are significant changes in both equipment selection and system operation. First, the introduction of charging loads substantially increases total electricity consumption, rising from 26,235 MWh (without EV charging) to about 27,550 MWh. To address peak demand during charging periods, the system requires increased battery energy storage capacity, from 6,600 kWh to 8,500 kWh. Additionally, the demand for charging infrastructure becomes prominent, requiring 210 charging piles. As a result, both the total system cost and carbon emissions increase, from 19.23 million RMB/year to 20.05 million RMB/year and from 13,937 tons/year to 14,621 tons/year, respectively. Overall, the integration of EV charging loads leads to higher investment and operational pressure, especially for storage and charging facilities.

Table.4 System configuration under different charging strategies

Dimension	Baseline (without charging load)	Uncoordinated Charging	Coordinated Charging
AC (kW)	0	0	0
EC (kW)	20800	20800	20800
ICS (kWh)	105600	105600	105600
Ice Maker Unit (kW)	13900	13900	13900
HX (kW)	4400	4400	3800
ASHP (kW)	5100	5100	5700
BES (kWh)	6600	8500	7000
CP (units)	0	210	144
Steam Consumption (MWh)	745	745	472
Electricity consumption (MWh)	26235	27550	27544
Carbon Emissions (tCO_2/year)	13937	14621	14510
Total Cost (10,000 RMB/year)	1923	2005	1977

A further comparison of uncoordinated and coordinated (orderly) charging strategies reveals that coordinated charging can effectively optimize system configuration. Compared with uncoordinated charging:

Charging infrastructure: Coordinated charging reduces the number of charging piles from 210 to 144 (a decrease of 31%), saving infrastructure investment.

Energy storage configuration: The required EES capacity decreases from 8,500 kWh to 7,000 kWh (an 18% reduction), mainly due to the smoothing of the load peak.

Heating system: Coordinated charging frees up more electricity for heating. The capacity of HXs decreases from 4,400 kW to 3,800 kW, while ASHP capacity increases from 5,100 kW to 5,700 kW. This means the system relies more on ASHPs and less on steam.

Cost and carbon emissions: The total annual cost decreases from 20.05 million RMB to 19.77 million RMB, and carbon emissions drop from 14,621 tons to 14,510 tons, achieving both economic and low-carbon benefits.

These results indicate that EV charging strategies have a significant impact on the equipment selection and operation of integrated energy systems. Uncoordinated charging, due to instantaneous load peaks, requires the system to be configured with higher peak power supply capacity and larger energy storage. In contrast, coordinated charging smooths the load and reduces the peak, which not only lowers the investment required for CPs and EESs, but also reduces dependence on high-carbon steam energy, thereby saving operating costs and reducing carbon emissions.

4. CONCLUSIONS

Based on a RIES case in Hangzhou, this study compares system configurations and performance under different optimization strategies.

Optimization of system configuration reduces both cost and emissions: Without considering EV charging loads, replacing ACs with ECs and CESs, and adding ASHPs and EESs, significantly improves system efficiency. The optimized system reduces annual cost from 37.35 million RMB to 19.43 million RMB and cuts annual carbon emissions by about 66%, highlighting the benefits of electrification and energy storage.

Coordinated charging improves flexibility and economy: With increasing EV penetration, if charging is not properly coordinated, the regional integrated energy system must deploy additional energy storage and charging infrastructure to meet peak demand, resulting in higher total costs and carbon emissions. In contrast, coordinated charging can significantly smooth load peaks, reducing the requirements for energy storage and charging infrastructure by 18% and 31%, respectively. Steam consumption further decreases by 37%, and both annual cost and carbon emissions are simultaneously reduced. Therefore, it is recommended that future RIES planning fully leverage the flexibility of EV loads and implement smart coordinated charging strategies to achieve low-carbon and efficient system operation.

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