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BI-OBJECTIVE PLANNING OF PARK ELECTROTHERMAL SYSTEMS WITH GEOTHERMAL, RENEWABLES AND STORAGE

Abstract: As wind and photovoltaic deployment in industrial parks approaches practical upper bounds, the central planning issue shifts from simply expanding renewable-electricity capacity to identifying where the remaining decarbonisation leverage exists. This study addresses this later-stage planning problem by developing a representative-day bi-objective planning model for an industrial park electricity-heat system integrating wind power, photovoltaic generation, geothermal heat utilisation, thermal energy storage (TES), battery storage, and bidirectional grid interaction, and solves it using multi-objective particle swarm optimisation. The results show that wind and photovoltaic capacities remain close to their feasible upper bounds across representative Pareto solutions, whereas the main structural variation occurs in geothermal deployment and thermal storage. From the carbon-oriented end to the economy-oriented end of the frontier, annualised capital expenditure (CAPEX) decreases from $(2691.10 \text{ to } 977.75) \cdot 10^4$ RMB, while carbon reduction decreases from $(24.808 \text{ to } 21.294) \cdot 10^4 \text{ t}_{\text{CO}_2}$ ($\text{t} = \text{tonne} = 10^6 \text{ g} = \text{Mg} = 10^3 \text{ kg}$) and the heat deficit ratio increases from 8.50 % to 36.46 %. The representative middle-frontier solution achieves a more balanced outcome, with an economic-efficiency index of 15.212, carbon reduction of $23.090 \cdot 10^4 \text{ t}_{\text{CO}_2}$, and a heat deficit ratio of 6.40 %. Winter representative-day operation shows that TES provides 48.8 % of heat demand, whereas medium- and high-temperature geothermal heat contribute 33.9 % and 10.7 % respectively; by contrast, geothermal electricity remains negligible. Additional heat-adequacy screening and TES cost-sensitivity analyses support the same interpretation. These results indicate that, once electricity-side renewable deployment is high, the main planning lever for balancing investment burden, decarbonisation performance, and heat-service adequacy shifts toward coordinated heat-side design in industrial parks.

Keywords: industrial park decarbonisation, electricity-heat integrated system, geothermal heat utilisation, thermal energy storage, representative-day modelling, pareto optimisation

Introduction

Industrial parks are increasingly being planned as integrated electricity-heat systems rather than as collections of isolated energy facilities [1]. In such systems, low-carbon transition is not simply a matter of adding more renewable equipment to an otherwise unchanged supply structure. Instead, it requires coordinated planning across electricity supply, heat supply, conversion devices, storage resources, and system operation. This shift is especially important at the industrial-park scale, where multiple loads are concentrated

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within a limited spatial boundary and where infrastructure sharing can materially affect both investment efficiency and emissions performance [2]. Reviews of energy hubs and multi-energy systems have shown that electricity-heat coupling can strongly reshape overall system efficiency, operating flexibility, and decarbonisation potential [3]. At the same time, industrial clusters provide a practical setting for cross-sector energy synergies because shared pipelines, substations, and storage resources can reduce duplication and improve the feasibility of coordinated low-carbon planning [4].

As renewable electricity penetration rises, however, the planning problem also changes. The key question is no longer only whether wind and photovoltaic capacity should be expanded, but whether the remaining decarbonisation leverage shifts toward heat-side resources once electricity-side renewable deployment approaches practical limits. In many industrial-park cases, wind and photovoltaic deployment cannot expand indefinitely because of practical upper bounds related to land availability, rooftop area, grid access, local acceptance, and system integration limits. Once these bounds are approached, the incremental value of simply adding more electricity-side renewable capacity tends to diminish. The central planning question then shifts from whether renewable electricity should be deployed to how the remaining mismatch between carbon reduction, cost control, and service performance should be resolved. Multi-objective studies of hybrid renewable systems have already shown that optimal outcomes are sensitive not only to renewable resource quality but also to how flexibility is represented in the planning model [5]. In coupled electricity-heat systems, thermal energy storage can absorb temporal mismatches that cannot be efficiently handled by electricity-side resources alone, thereby improving renewable integration and reducing heat-network balancing pressure [6, 7]. Design-oriented studies further suggest that thermal storage is not merely an operational add-on; it can change the preferred system configuration itself [8]. This is consistent with operational studies showing that storage management materially affects supply-demand balancing, and with broader district-heating research indicating that future low-carbon heat systems will rely more heavily on diversified heat sources and stronger storage coordination [9, 10]. Similar conclusions have been reported for borehole thermal energy storage combined with district heating, reinforcing the argument that heat-side flexibility is a structural issue rather than a secondary refinement [11].

Geothermal energy is particularly relevant in this context because its role differs fundamentally from that of variable wind and photovoltaic generation. Unlike intermittent electricity-side renewables, geothermal resources provide relatively stable thermal output and can therefore support the heat side more directly. Reviews of worldwide geothermal deployment have shown that direct-use geothermal applications are already important in district heating and other heat-demand sectors [12]. Studies comparing geothermal applications at different depths further suggest that the value of geothermal resources depends less on the resource alone than on how well the thermal grade matches the end-use demand and how effectively the resource is integrated into the broader energy system [13]. For integrated electricity-heat systems, this also means that geothermal resources should not be evaluated only by resource availability or installed capacity. Their planning value depends on whether the thermal grade matches the end-use heat demand and whether storage can help align relatively stable geothermal output with time-varying heat loads. TES is therefore important because it improves the temporal match between geothermal heat supply and load demand. Research on deep borehole heat exchangers has also expanded the range of locations where geothermal utilisation may be considered feasible,

even outside conventional hydrothermal regions [14]. More generally, geothermal technologies are increasingly being evaluated as components of long-term integrated low-carbon systems rather than as stand-alone resource projects [15]. At the same time, life-cycle and environmental assessments caution against assuming that geothermal deployment is universally advantageous under all engineering conditions or system boundaries [16-18]. This makes geothermal planning a system-integration problem as much as a resource-development problem. It is also necessary to distinguish between geothermal power conversion and geothermal direct heat use in integrated energy planning. In systems where wind and photovoltaic generation already provide a large share of low-carbon electricity, the marginal value of converting geothermal heat into electricity may be limited by conversion efficiency and investment cost. By contrast, direct geothermal heat use can provide stable heat-side substitution, particularly when combined with TES to shift relatively stable geothermal output to periods of higher heat demand.

These observations point to a specific gap in current planning research. Existing studies have made substantial progress in modelling sector-coupled systems, renewable integration, thermal storage, and geothermal deployment. Policy and implementation research has also highlighted the importance of regulation, investment conditions, and deployment barriers in low-carbon heat infrastructure [19, 20]. In parallel, model-based decarbonisation studies have shown that the economic value of energy technologies depends strongly on how system-level cost-emission trade-offs are resolved [21]. However, most existing studies still discuss these technologies from the perspective of component integration or capacity expansion. Less attention has been paid to how the dominant planning lever changes after electricity-side renewable deployment has already approached practical limits. This distinction is important because, under a later-stage renewable-electricity planning context, the marginal value of additional wind and photovoltaic capacity may decline, while heat-side substitution, thermal-grade matching, and storage-based temporal coordination may become more decisive for system-level performance. Yet one transition remains insufficiently clarified: once wind and photovoltaic capacities are already close to their practical upper bounds, where does the main room for further improvement actually remain? Under these conditions, the planning issue is no longer simply whether more renewable electricity should be installed. The more consequential question is whether the remaining leverage shifts toward heat-side substitution, temporal coordination, and service adequacy. For this type of planning-oriented problem, representative-day aggregation offers a useful compromise between fidelity and tractability because it can preserve the main seasonal differences in resource availability and demand without requiring full-year chronological optimisation [22].

This study addresses that gap by developing a representative-day bi-objective planning model for an industrial park electricity-heat system integrating wind power, photovoltaic generation, geothermal heat utilisation, thermal energy storage, battery storage, and bidirectional grid interaction, and solving the resulting problem using multi-objective particle swarm optimisation [23]. The analysis is organised around three questions. First, how does the cost-carbon trade-off evolve once electricity-side renewable deployment is already high? Second, does the main capacity adjustment along the Pareto frontier shift from the electricity side to the heat side under such conditions? Third, why does the middle section of the frontier offer more planning value than the extreme endpoints? By answering

these questions, the paper aims to clarify the role of geothermal heat and TES in industrial-park planning under high renewable-electricity penetration.

The originality of this study therefore lies not in claiming that wind, solar, geothermal, or storage technologies are individually beneficial in a generic sense, but in clarifying how the center of gravity of system optimisation changes under a later-stage renewable-electricity deployment context. Specifically, this study makes three contributions. First, it frames industrial-park electricity-heat planning under practical wind and photovoltaic deployment limits, thereby shifting the research focus from additional electricity-side expansion to the identification of remaining system-level leverage. Second, it distinguishes the planning roles of geothermal direct heat use, geothermal power conversion, TES, and BES within a unified electricity-heat optimisation framework. Third, it interprets the Pareto frontier not only through economic efficiency and carbon reduction, but also through heat-service adequacy, thereby linking mathematical non-dominated solutions with practical planning acceptability.

Materials and methods

To examine how the remaining configuration flexibility changes once wind and photovoltaic deployment is already high, a planning model was developed for an industrial park electricity-heat system integrating wind power, photovoltaic generation, geothermal heat utilisation, thermal energy storage (TES), battery energy storage (BES), geothermal power conversion, auxiliary heating, and bidirectional grid interaction. Rather than treating geothermal energy as an isolated renewable option, the model evaluates it as a heat-side substitution resource whose planning value depends on its interaction with storage and residual grid dependence. Capacity planning and system operation are linked through a representative-day framework so that long-term investment decisions and short-term balancing requirements can be assessed within one consistent model. The system structure is shown in Figure 1.

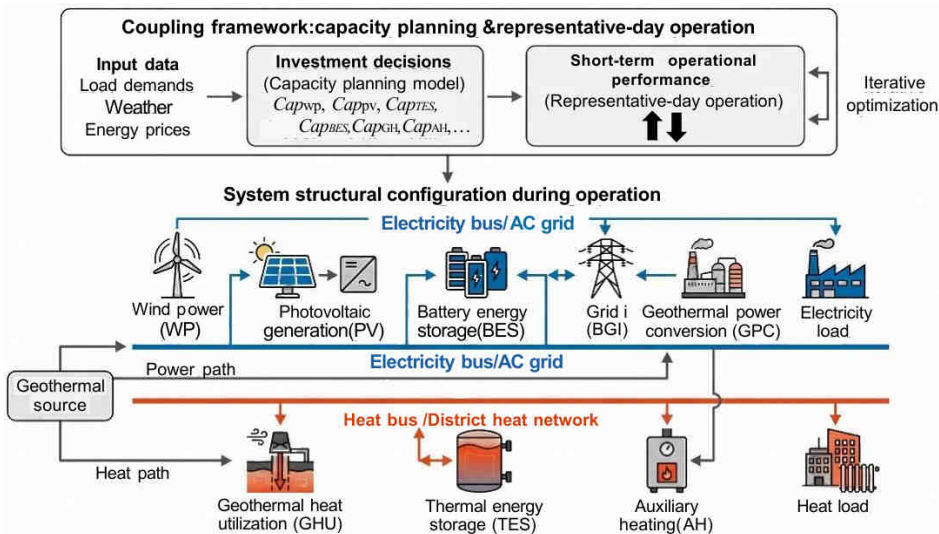


Fig. 1. Structural configuration of the electricity-heat system for the low-carbon industrial park

Within this structure, the electricity side is balanced mainly through wind, photovoltaic generation, battery storage, and grid exchange, whereas the heat side is balanced mainly through geothermal direct-use heat, TES, and auxiliary heating. Under the present system setting, geothermal power conversion represents a secondary branch rather than the dominant utilisation pathway of geothermal resources.

Demand representation and representative-day aggregation

To preserve the main seasonal characteristics of park operation while avoiding full-year chronological optimisation, the annual system is represented by several representative days. The selected representative days correspond to typical seasonal positions in the annual operating profile and are used to represent spring, summer, autumn, and winter operating conditions. Their weights indicate the number of equivalent days represented by each typical day when hourly operating results are scaled to annual values. The annual equivalent of an operating variable is calculated by weighting the hourly results of each representative day, as shown in Eq. (1), where ω_k denotes the weight of representative day k and h denotes the hourly index. The daily total demand is then described by Eq. (2), in which D_0 is the baseline daily demand, A is the park area and q_E is the electricity intensity, d_k is the calendar day represented by k , and α_D , ϕ_D , and ε_k denote the seasonal amplitude, phase parameter, and disturbance term, respectively. Based on this daily demand, the hourly electricity and heat loads are obtained through normalised load profiles, as given in Eq. (3), where β_H is the heat-demand share, and ψ_h^E and ψ_h^H are the normalised hourly electricity and heat load profiles.

$$X^{\text{ann}} = \sum_{k \in \mathcal{K}} \omega_k \sum_{h=1}^{24} X_{k,h} \quad (1)$$

$$D_k = D_0 \left[1 + \alpha_D \sin \left(\frac{2\pi(d_k - \phi_D)}{365} \right) \right] + \varepsilon_k, D_0 = A q_E \quad (2)$$

$$L_{k,h}^E = (1 - \beta_H) D_k \psi_h^E, \quad L_{k,h}^H = \beta_H D_k \psi_h^H \quad (3)$$

This treatment retains the seasonal differences most relevant to planning while keeping the optimisation problem tractable. Accordingly, the representative-day framework is used here to connect installed-capacity decisions with typical electricity-heat balancing conditions rather than to reproduce all hourly fluctuations of the full year.

Renewable generation and reference system

Wind and photovoltaic generation are represented through availability factors, as defined in Eq. (4), where $\rho_{r,k}$ is the availability factor of renewable source r on representative day k , $\bar{\rho}_r$ is average availability factor, $\rho_r^{\max}$ is its upper bound, α_r and ϕ_r describe seasonal variation, and $\xi_{r,k}$ is the disturbance term. The corresponding hourly renewable output is calculated by Eq. (5), where C_r denotes installed capacity and ψ_h^r is the normalised hourly generation profile. In this way, renewable supply depends jointly on

installed scale and representative-day resource conditions. In the present case setting, the upper bounds of wind and photovoltaic capacities are used to represent a later-stage renewable-electricity planning context. These bounds reflect practical deployment constraints such as available land, rooftop potential, grid-connection capacity, and local system-integration limits. Therefore, high renewable-electricity penetration is first embedded in the case setting through practical capacity limits, and the optimisation results are then used to examine whether wind and photovoltaic capacities remain close to these limits.

$$\rho_{r,k} = \min \left\{ \rho_r^{\max}, \max \left[0, \bar{\rho}_r \left(1 + \alpha_r \sin \left(\frac{2\pi(d_k - \phi_r)}{365} \right) \right) + \xi_{r,k} \right] \right\} \quad (4)$$

$$P_{k,h}^r = C_r \rho_{r,k} \psi_h^r \quad (5)$$

To provide a transparent benchmark, a reference system is introduced in which all electricity demand is purchased from the grid and all heat demand is supplied by auxiliary heating. Its annual cost and annual carbon emission are given by Eq. (6) and (7), where $p_{k,h}^{\text{buy}}$ is the electricity-purchase tariff, c^{aux} is the auxiliary-heating cost, and $\gamma_{k,h}^{\text{grid}}$ and γ^{aux} are the corresponding emission factors of grid electricity and auxiliary heat. This benchmark is used as the basis for evaluating the economic and carbon performance of the integrated system.

$$C^{\text{ref}} = \sum_k \omega_k \sum_h \left(p_{k,h}^{\text{buy}} L_{k,h}^E + c^{\text{aux}} L_{k,h}^H \right) \quad (6)$$

$$E^{\text{ref}} = \sum_k \omega_k \sum_h \left(\gamma_{k,h}^{\text{grid}} L_{k,h}^E + \gamma^{\text{aux}} L_{k,h}^H \right) \quad (7)$$

Geothermal heat, storage coupling, and energy balance

Geothermal resources are represented by three thermal grades, and their extraction is constrained jointly by installed capacity and annual availability, as expressed in Eq. (8). Here, $Q_{j,k,h}^g$ denotes the extracted geothermal heat of grade j , C_j^g is the corresponding installed extraction capacity, and $E_j^{\max}$ is the annual extraction cap. This formulation reflects that geothermal deployment is limited not only by conversion equipment but also by long-term resource availability.

$$0 \leq Q_{j,k,h}^g \leq C_j^g, \quad \sum_k \omega_k \sum_h Q_{j,k,h}^g \leq E_j^{\max} \quad (8)$$

Geothermal power generation is described by Eq. (9), where $Q_{k,h}^P$ is the thermal input for power conversion, η_{HP} is the heat-to-power efficiency, $P_{k,h}^g$ is geothermal power output, and C_P is the installed geothermal power-generation capacity. TES and BES are introduced as the main flexibility resources on the heat side and the electricity side, respectively. Their state transitions are given by Eq. (10) and Eq. (11), where $S_{k,h}$ and

$B_{k,h}$ denote the TES state and battery state of charge, $Q_{k,h}^{\text{ch}}$ and $Q_{k,h}^{\text{dis}}$ represent TES charging/discharging rates, $P_{k,h}^{B,\text{ch}}$ and $P_{k,h}^{B,\text{dis}}$ represent BES charging and discharging power, and C_S and C_B are the corresponding storage capacities. These equations capture the intertemporal shifting of thermal and electrical energy within the representative-day framework.

$$P_{k,h}^g = \eta_{HP} Q_{k,h}^P, \quad P_{k,h}^g \leq C_P \quad (9)$$

$$S_{k,h} = S_{k,h-1} + \eta_S^{\text{ch}} Q_{k,h}^{\text{ch}} - \frac{Q_{k,h}^{\text{dis}}}{\eta_S^{\text{dis}}}, \quad 0 \leq S_{k,h} \leq C_S \quad (10)$$

$$B_{k,h} = B_{k,h-1} + \eta_B^{\text{ch}} P_{k,h}^{B,\text{ch}} - \frac{P_{k,h}^{B,\text{dis}}}{\eta_B^{\text{dis}}}, \quad 0 \leq B_{k,h} \leq C_B \quad (11)$$

On this basis, the coupled electricity-heat balances are enforced through Eq. (12). In the electricity balance, renewable generation, geothermal power, battery discharge, and grid purchase jointly meet electricity demand, storage charging, grid sale, and possible curtailment. In the heat balance, geothermal direct-use heat, TES discharge, and auxiliary heating jointly satisfy heat demand and storage charging. The main variables here are $P_{k,h}^{\text{buy}}$, $P_{k,h}^{\text{sell}}$, and $P_{k,h}^{\text{curt}}$ for grid purchase, grid sale, and curtailed electricity, and $Q_{k,h}^{\text{dir}}$ and $Q_{k,h}^{\text{aux}}$ for geothermal direct-use heat and auxiliary heat. This part of the model is central because it determines whether the main configuration adjustment under high renewable penetration occurs on the electricity side or on the heat side.

$$\begin{aligned} P_{k,h}^w + P_{k,h}^s + P_{k,h}^g + P_{k,h}^{B,\text{dis}} + P_{k,h}^{\text{buy}} &= L_{k,h}^E + P_{k,h}^{B,\text{ch}} + P_{k,h}^{\text{sell}} + P_{k,h}^{\text{curt}} \\ Q_{k,h}^{\text{dir}} + Q_{k,h}^{\text{dis}} + Q_{k,h}^{\text{aux}} &= L_{k,h}^H \end{aligned} \quad (12)$$

This coupled-balance formulation is essential because it determines whether the remaining planning flexibility under high renewable penetration is absorbed primarily by electricity-side assets or reallocated toward heat-side substitution and temporal coordination.

Objective functions and multi-objective particle swarm optimisation (MOPSO)

The optimisation problem is formulated as a bi-objective model. The first objective, given in Eq. (13), is an economic-efficiency index defined relative to the reference system, where C^{ref} is the annual cost of the reference system, C^{sys} is the annual net system cost after integrated deployment, and C^{cap} is the annualised capital cost. Rather than measuring cost alone, this indicator reflects the economic benefit obtained per unit of annualised capital burden under the selected capacity portfolio.

$$\max J_1 = \frac{C^{\text{ref}} - C^{\text{sys}}}{C^{\text{cap}}} \quad (13)$$

$$\max J_2 = E^{\text{ref}} - E^{\text{grid}} - E^{\text{aux}} - \lambda^{\text{curt}} E^{\text{curt}} \quad (14)$$

The second objective, given in Eq. (14), is annual carbon reduction relative to the reference system, where E^{ref} is the annual carbon emission of the reference system, E^{grid} is the grid-related carbon emission, E^{aux} is the auxiliary-heating carbon emission, E^{curt} is the curtailment-related penalty term, and λ^{curt} is the corresponding coefficient. The resulting bi-objective problem is solved using Multi-Objective Particle Swarm Optimisation (MOPSO), in which each particle represents one candidate capacity vector and an external archive stores non-dominated solutions.

Table 1

Key case-study parameters

Item	Symbols and units	Values
Park area; electricity intensity	$A[\text{ha}], q_E[\text{MWh} \cdot \text{ha}^{-1} \cdot \text{d}^{-1}]$	50; 50
Baseline demand; heat share	$D_0[\text{MWh} \cdot \text{d}^{-1}]; \beta_H[-]$	2500; 0.30
Representative days	$d_k[\text{d}]$	79/171/265/355
Representative-day weights	$\omega_k[\text{d}]$	90/92/93/90
Wind/solar average availability	$\bar{\rho}_w, \bar{\rho}_s[-]$	0.24/0.15
Geothermal extraction caps	$E_H^{\text{max}}, E_M^{\text{max}}, E_L^{\text{max}}[\text{MWh} \cdot \text{a}^{-1}]$	74,400/186,000/111,600
Geo heat-to-power efficiency	$\eta_{\text{HP}}[-]$	0.15
TES/BES charge-discharge efficiency	$\eta_S^{\text{ch}}, \eta_S^{\text{dis}}, \eta_B^{\text{ch}}, \eta_B^{\text{dis}}[-]$	0.95/0.95/0.95/0.95
Buy/sell price; backup heat cost	$p^{\text{buy}}, p^{\text{sell}}, c^{\text{aux}}[\text{RMB} \cdot \text{MWh}^{-1}]$	520/180/600
Grid/heat emission factors	$\gamma^{\text{grid}}, \gamma^{\text{aux}}[\text{t}_{\text{CO}_2} \cdot \text{MWh}^{-1}]$	0.57/0.57
Unit CAPEX coefficients used in C_{cap}	$\text{Wind} / \text{PV} / \text{wellfield} / \text{geo}[\text{RMB} \cdot \text{MW}^{-1}],$ $\text{TES} / \text{BES}[\text{RMB} \cdot \text{MWh}^{-1}]$	260,000/235,000/550,000/ 2,100,000; 30,000/70,000
Discount rate	$i[-]$	0.08

Heat-service adequacy is not introduced as a third optimisation objective in the present formulation. Instead, it is evaluated after optimisation through a screening procedure. This design is used for two reasons. First, the bi-objective formulation allows the basic cost-carbon trade-off to be identified clearly without dispersing the Pareto interpretation into a higher-dimensional objective space. Second, heat adequacy is treated as a practical acceptability condition: a solution may be non-dominated in the cost-carbon space, but it should not be considered practically acceptable if it allows an excessive heat deficit.

The screening procedure is therefore used to connect mathematical non-dominance with planning acceptability. To further test the robustness of the heat-side interpretation, additional analyses are conducted through heat-adequacy screening and TES CAPEX sensitivity. The key case-study parameters used in the numerical simulation are summarised in Table 1.

Results and discussion

The results are discussed with a focus on structural interpretation rather than on isolated numerical comparison. The central issue is not only whether different Pareto solutions exist, but what those solutions imply about the remaining leverage of system planning under high renewable-electricity penetration. Across the following subsections, the discussion therefore moves from frontier shape, to capacity migration, to operational mechanism, and finally to robustness checks on adequacy and TES cost.

Frontier characteristics under high renewable penetration

The updated base-case results reveal a clear trade-off between economic efficiency and carbon reduction. Five representative Pareto solutions are denoted as S1-S5, ordered from the carbon-oriented end to the economy-oriented end of the frontier. As presented in Figure 2 and Table 2, moving from S1 to S5 increases the economic-efficiency index from 8.683 to 21.409, while annual carbon reduction decreases from $(24.808 \pm 21.294) \cdot 10^4 \text{ tCO}_2$. Over the same range, annualised CAPEX declines sharply from $2691.10 \cdot 10^4 \text{ RMB}$ to $977.75 \cdot 10^4 \text{ RMB}$, whereas annual net saving changes within a narrower band. This indicates that the Pareto frontier is shaped primarily by differences in capital commitment rather than by large changes in annual operating benefit.

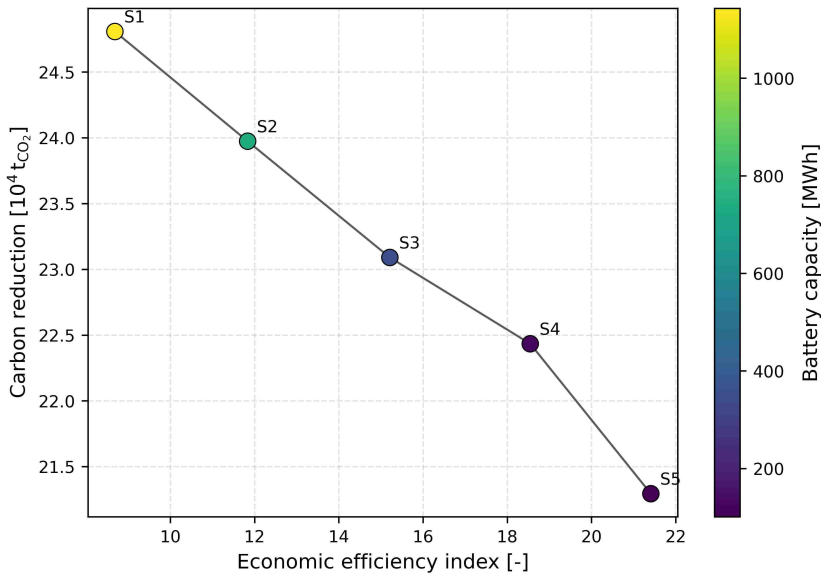


Fig. 2. Pareto frontier of economic efficiency and annual carbon reduction

Table 2

Summary performance of representative Pareto solutions

Scenario	Economic efficiency index [-]	Carbon reduction [10^4 t _{CO₂}]	Annualised CAPEX [10^4 RMB]	Annual net saving [10^4 RMB]	Heat deficit ratio [%]	Heat coverage ratio [%]
S1	8.683	24.808	2,691.10	23,365.92	8.50	91.50
S2	11.835	23.974	1,947.76	23,051.18	6.51	93.49
S3	15.212	23.090	1,516.88	23,074.50	6.40	93.60
S4	18.545	22.434	1,229.41	22,799.22	5.85	94.15
S5	21.409	21.294	977.75	20,933.15	36.46	63.54

Table 2 also suggests that the frontier should not be interpreted as a search for a single best solution. The carbon-oriented endpoint achieves the largest emission reduction, but only at the cost of a much higher investment burden. By contrast, the economy-oriented endpoint improves the economic-efficiency index mainly through lower CAPEX, while its heat-service performance deteriorates substantially. The middle part of the frontier is therefore more informative from a planning perspective, because it reflects solutions that retain most of the carbon-reduction benefit without requiring the highest capital intensity.

Among the representative solutions, S3 is selected for detailed operational analysis because it provides a clearer representation of the middle-frontier compromise rather than because it is optimal in every individual indicator. Compared with S1, S3 substantially reduces annualised CAPEX while retaining a relatively high carbon-reduction level. Compared with S4, S3 has a lower economic-efficiency index but achieves a higher carbon reduction and is closer to the central transition between the carbon-oriented and economy-oriented parts of the frontier. Therefore, S3 is used as an interpretive case to explain the operating mechanism of a balanced solution, rather than as a universal optimum among all Pareto solutions.

Capacity migration toward the heat side

The capacity patterns along the Pareto frontier indicate that the main structural adjustment occurs on the heat side rather than on the electricity side. As shown in Figure 3, wind and photovoltaic capacities remain close to their feasible upper bounds across all representative solutions, whereas the total number of geothermal wells decreases markedly from 62 in S1 to 12 in S5. At the same time, TES remains consistently large, varying only between 273 MWh and 300 MWh, while geothermal power generation stays limited at (0-4) MW.

This pattern is important for interpreting the frontier. It also clarifies the relationship between the case setting and the optimisation outcome. The practical upper bounds on wind and photovoltaic capacity define a planning context in which further electricity-side renewable expansion is constrained. The optimised solutions then show that wind and photovoltaic capacities remain close to these feasible upper bounds across the Pareto frontier. Therefore, the high-renewable condition is both a case-setting premise and a result-supported interpretation. Since wind and solar capacities change little across the

representative solutions, additional electricity-side renewable expansion no longer acts as the main differentiating factor once renewable deployment is already high. Instead, the remaining planning flexibility is mainly absorbed by geothermal deployment and heat-side coordination. The decline in well number from the carbon-oriented end to the economy-oriented end shows that the system reduces heat-side substitution intensity when moving toward lower-capital solutions.

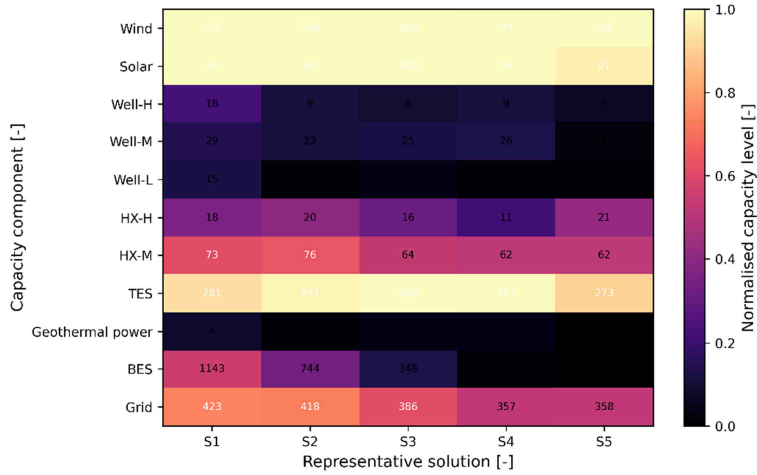


Fig. 3. Heat-side capacity migration of representative Pareto solutions

At the same time, the persistently large TES capacity indicates that heat-side temporal flexibility remains essential across the frontier. In other words, what changes most is the scale of geothermal deployment, not the need for thermal coordination itself. This supports the interpretation that geothermal resources are valued mainly for direct heat substitution, while TES provides the flexibility required to align relatively stable geothermal output with time-varying heat demand. Under the present parameter setting, geothermal electricity plays only a minor role in this configuration logic.

The limited role of geothermal electricity can be explained by the relative value of geothermal heat under the present system setting. First, the assumed heat-to-power conversion efficiency is relatively low, which weakens the advantage of converting geothermal heat into electricity. Second, wind and photovoltaic generation already provide a large share of low-carbon electricity, reducing the marginal value of additional geothermal electricity on the power side. Third, heat demand remains a major service requirement in the industrial park, and TES enables relatively stable geothermal heat to be shifted to periods of higher heat demand. Therefore, geothermal resources are more valuable in this case as heat-side substitution resources than as electricity-generation resources. This finding should not be generalised to all geothermal systems, but it is consistent with the specific high-renewable electricity context considered in this study.

Economic-carbon implications and heat-service adequacy

The economic decomposition in Figure 4a shows that grid-purchase cost remains the dominant expenditure item across all representative solutions. Meanwhile, the rise in the economic-efficiency index toward the economy-oriented end is driven mainly by the decline in annualised CAPEX rather than by a substantial increase in annual operating gain. This means that the apparent economic advantage of the right-hand side of the frontier should be interpreted as a lower-capital strategy, not as a fundamentally superior overall system outcome.

The carbon decomposition in Figure 4b leads to a similar conclusion. Avoided grid-related emissions remain the largest contributor to total carbon reduction, declining from $19.345 \cdot 10^4 \text{ t}_{\text{CO}_2}$ in S1 to $16.652 \cdot 10^4 \text{ t}_{\text{CO}_2}$ in S5. Avoided backup-heat emissions form the second major contribution, decreasing from $(5.463 \text{ to } 4.642) \cdot 10^4 \text{ t}_{\text{CO}_2}$. Curtailment penalty is negligible in all representative solutions. Taken together, these results indicate that the system's carbon performance depends not only on electricity-side renewable supply, but also on the extent of heat-side substitution.

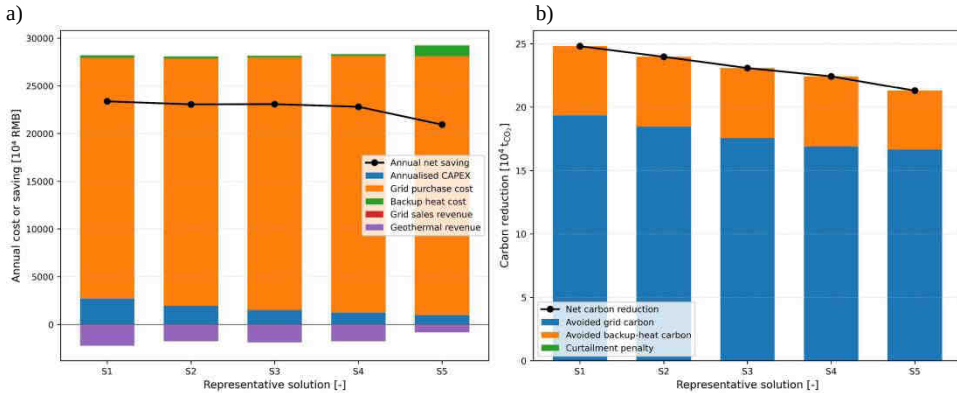


Fig. 4. Economic and carbon-performance decomposition of representative solutions: a) economic breakdown; b) carbon-reduction breakdown

Heat-service adequacy further changes how the frontier should be interpreted. The economy-oriented endpoint S5 achieves the highest economic-efficiency index, but its heat deficit ratio rises to 36.46 %, far above the level of the middle-frontier solutions. This suggests that part of its economic attractiveness is obtained by accepting substantial heat-service degradation. Therefore, the practically relevant trade-off is not simply between economic efficiency and carbon reduction, but among investment burden, decarbonisation performance, and heat-service adequacy.

Operating mechanism of the middle-frontier solution

To explain why the middle section of the frontier is more attractive for planning, the representative middle-frontier solution S3 is examined in more detail. Winter representative-day operation is particularly informative because heat-side differentiation is most pronounced during the heating season.

On the heat side, the winter dispatch results in Figure 5 show that TES provides the largest share of heat demand, accounting for 48.8 %. Medium-temperature geothermal heat contributes 33.9 %, high-temperature geothermal heat contributes 10.7 %, and backup heat accounts for only 6.6 %. This confirms that TES is not a marginal auxiliary component, but the key flexibility resource that shifts geothermal heat to periods of higher demand. The heat-side structure of S3 therefore reflects coordinated geothermal utilisation rather than direct one-to-one matching between resource output and heat load.

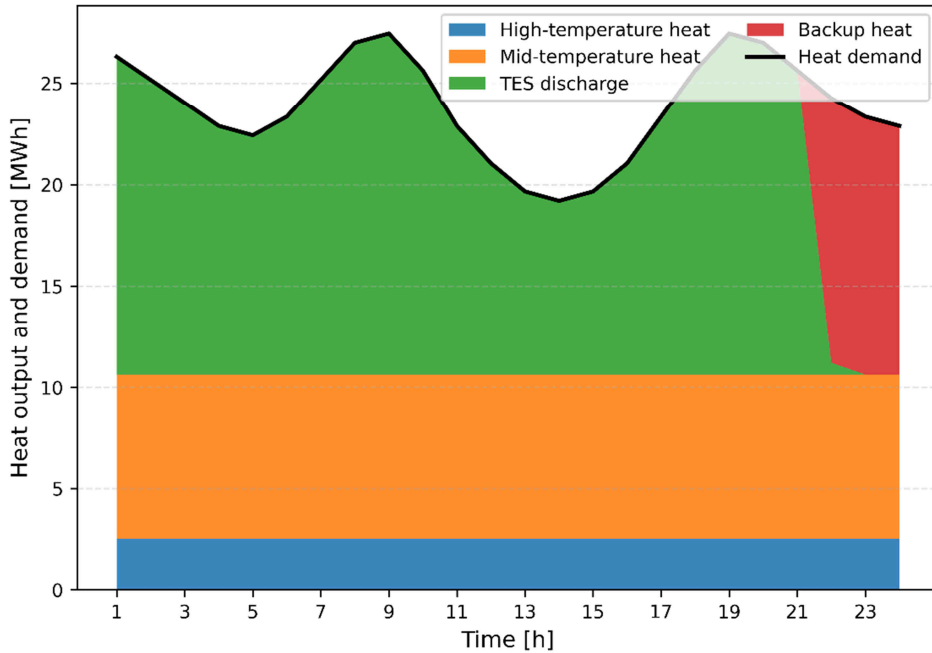


Fig. 5. Winter typical-day heat dispatch of the middle-frontier solution

The electricity-side dispatch in Figure 6 presents a different pattern. Wind and solar remain the dominant low-carbon electricity sources, supplying 37.5 % and 33.2 % of winter electricity demand, respectively. Battery discharge contributes 7.4 %, while grid purchase still accounts for 30.1 %. Geothermal electricity remains negligible. This does not mean that geothermal power conversion is universally unimportant. Rather, it reflects the specific planning context considered here, where low-carbon electricity is already largely supplied by wind and photovoltaic generation, while stable geothermal heat has greater value in reducing backup heat reliance. This indicates a clear functional division within the system: the electricity side is balanced primarily by wind, solar, BES, and the grid, whereas the heat side relies mainly on geothermal direct-use heat and TES.

This operating mechanism explains the broader planning results. The middle-frontier solution is attractive not because it maximises a single indicator, but because it combines high carbon-reduction performance with relatively low heat deficit and a moderate capital burden. In this sense, the winter representative day helps explain why the annual planning

preference shifts toward coordinated heat-side design once renewable-electricity deployment is already high.

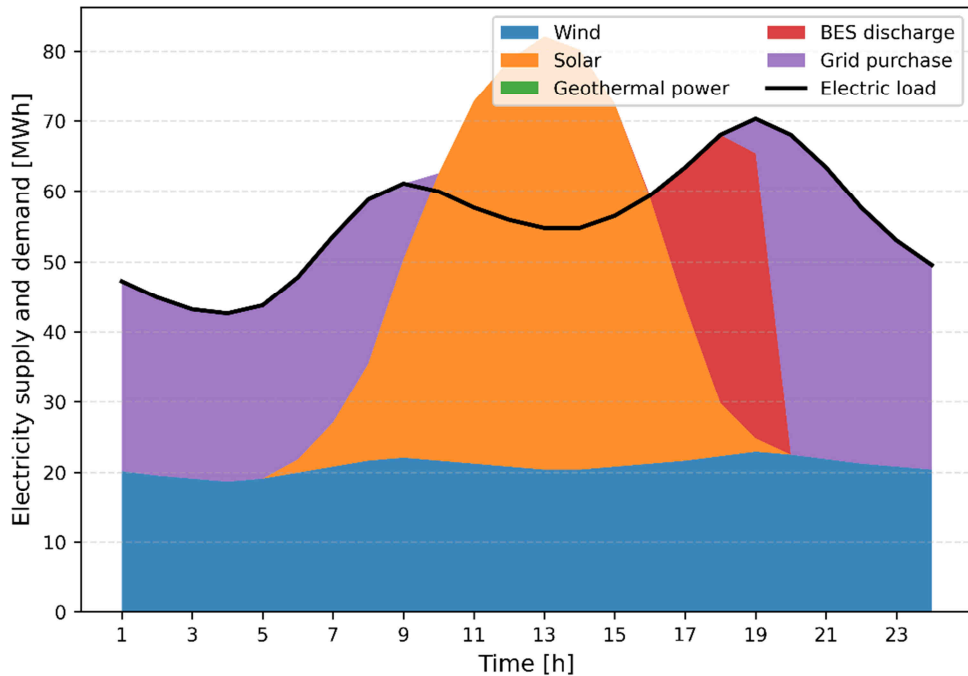


Fig. 6. Winter typical-day electric dispatch of the middle-frontier solution

Heat-adequacy screening of Pareto solutions

The role of heat-service adequacy can be evaluated more directly through post-screening of the non-dominated solutions. This screening step is not intended to create another optimisation objective, but to distinguish mathematically non-dominated solutions from practically acceptable planning solutions. As shown in Figure 7, applying a heat-deficit threshold removes the economy-oriented tail of the original Pareto frontier, where heat-service performance deteriorates rapidly. Out of 34 non-dominated solutions, 27 satisfy the adequacy requirement, whereas 7 are excluded.

This result is important because it shows that the economically attractive tail of the original frontier is partly supported by unacceptable heat-service performance. In other words, some low-capital solutions appear favourable only because they tolerate a level of heat deficit that would be difficult to justify in practical planning. The adequacy screen therefore helps distinguish between mathematically non-dominated solutions and solutions that remain plausible from a service perspective.

At the same time, the screened frontier still preserves a stable middle region. This means that the planning value of middle-frontier solutions is not an artifact of allowing poor heat-service adequacy. Even after excluding inadequacy-prone solutions, the middle

part of the trade-off frontier remains the most meaningful region for balancing cost, carbon reduction, and service performance.

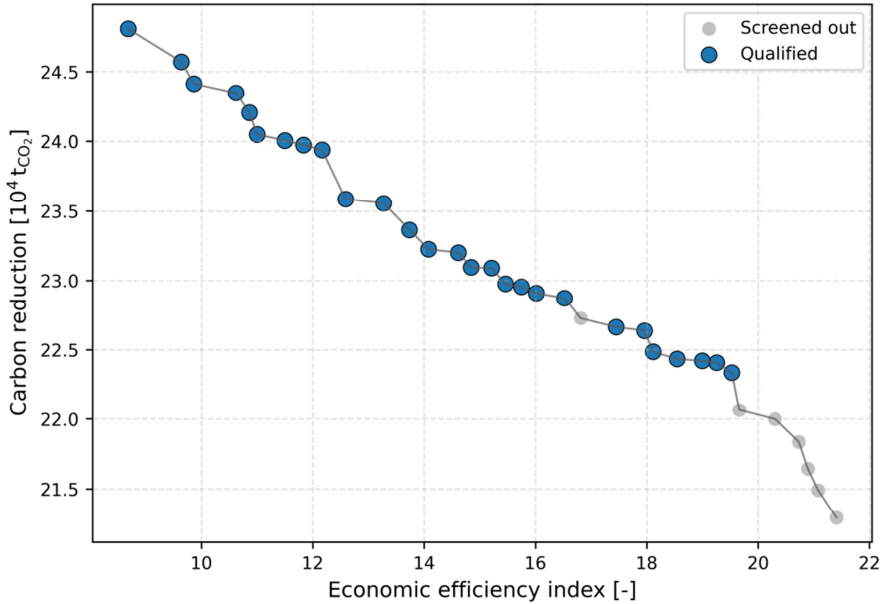


Fig. 7. Pareto frontier before and after heat-adequacy screening

TES CAPEX sensitivity of the middle-frontier solution

To test whether the heat-side interpretation is robust to changes in storage economics, TES CAPEX is varied by $\pm 20\%$ around the base value. As shown in Table 3, carbon reduction remains within a narrow range of $(22.397 - 22.512) \cdot 10^4 t_{CO_2}$, and the heat deficit ratio remains between 6.18 % and 7.13 % across the three cases. At the same time, TES capacity remains close to 290 MWh in all scenarios.

Table 3

TES CAPEX sensitivity of the middle-frontier solution

TES CAPEX multiplier	Economic efficiency [-]	Carbon reduction [$10^4 t_{CO_2}$]	Heat deficit ratio [%]	TES [MWh]	Total wells [-]	Battery [MWh]	Grid [MW]
0.80	19.56	22.512	7.13	291.00	33.00	151.00	285.00
1.00	18.21	22.397	7.01	290.00	43.00	128.00	238.00
1.20	18.59	22.480	6.18	295.00	36.00	142.00	340.00

These results suggest that the role of TES is structural rather than incidental. Changes in TES CAPEX do affect the exact mix of wells, battery capacity, and grid capacity, but they do not eliminate the need for a large thermal-storage component in the middle-frontier

solution. The persistence of TES across the sensitivity cases indicates that heat-side temporal shifting remains essential under the present system conditions.

Overall, the sensitivity analysis reinforces the main conclusion of this study. Once wind and photovoltaic deployment is already high, the remaining planning leverage no longer comes mainly from further electricity-side expansion. Instead, it depends primarily on how geothermal heat and TES are coordinated to balance capital burden, decarbonisation performance, and heat-service adequacy.

Conclusion

This study developed a representative-day bi-objective planning framework for an industrial park electricity-heat system integrating wind power, photovoltaic generation, geothermal heat utilisation, thermal energy storage, battery storage, and bidirectional grid interaction. By linking capacity configuration with representative-day operation, the model was used to examine how the cost-carbon trade-off evolves once electricity-side renewable deployment is already close to its practical upper range.

The results show that the main structural variation along the Pareto frontier does not come from further expansion of wind and photovoltaic capacity, which remains near the feasible upper bounds across representative solutions. Instead, the dominant adjustment occurs on the heat side, mainly through changes in geothermal deployment, heat-exchange capacity, and thermal storage. Under the present parameter setting, geothermal energy contributes primarily through direct heat substitution rather than electricity generation, while thermal energy storage acts as the key flexibility resource that shifts relatively stable geothermal heat output to periods of higher heat demand.

The results also indicate that the middle section of the Pareto frontier is more informative for planning than either extreme endpoint. Compared with the carbon-oriented end, middle-frontier solutions retain most of the carbon-reduction benefit while substantially lowering annualised capital cost. Compared with the strongly economy-oriented end, they avoid the marked deterioration in heat-service adequacy reflected by the sharp increase in heat deficit ratio. This means that the relevant planning trade-off is not only between cost and carbon reduction, but also between investment burden, decarbonisation performance, and the adequacy of heat supply.

The adequacy-screening results further strengthen this conclusion. After excluding non-dominated solutions with insufficient heat-service performance, the economically extreme tail of the frontier is substantially reduced, whereas the middle region remains broadly intact. This shows that the planning value of the middle-frontier region is not an artifact of allowing poor heat-service performance, but a robust feature of the system configuration problem under high renewable penetration.

The TES cost-sensitivity analysis leads to a similar interpretation. Moderate variation in TES capital cost changes the exact combination of heat-side assets, but does not eliminate the need for a relatively large thermal-storage component in the middle-frontier solution. This suggests that the role of TES is structural rather than incidental. Once renewable-electricity deployment is already high, the remaining room for meaningful system improvement depends mainly on coordinated heat-side design rather than on additional electricity-side expansion alone.

The present findings should be interpreted within the scope of a planning-level study. The model uses representative-day aggregation to describe seasonal operation and

simplifies geothermal resource behaviour through capacity and annual-availability constraints. As a result, it does not fully capture chronological full-year operation, detailed subsurface dynamics, or broader uncertainty in prices, resource conditions, and demand evolution. The planning implication is therefore most applicable to industrial parks where wind and photovoltaic deployment has already approached practical capacity limits, heat demand remains a major energy-service requirement, and stable heat-side resources such as geothermal heat are available for integration. In early-stage renewable deployment contexts, or in parks with limited heat demand or insufficient geothermal resources, further electricity-side renewable expansion may still remain the dominant planning measure. Future work may extend the framework by incorporating full-year chronological simulation, more detailed geothermal process representation, and broader uncertainty analysis. For planning practice, this implies that industrial parks that have already reached high levels of renewable-electricity deployment should prioritise geothermal heat coordination and heat-side flexibility enhancement before pursuing further marginal expansion on the electricity side alone. Even so, the results reported here provide a clear planning implication: for industrial parks that have already achieved high renewable-electricity penetration, the main lever for balancing investment burden and decarbonisation performance shifts increasingly toward geothermal heat utilisation and thermal-storage coordination.

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