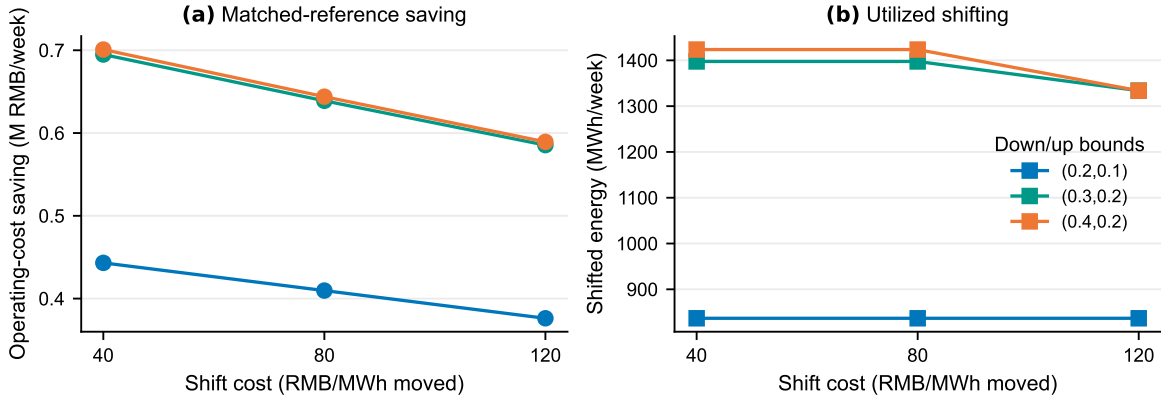


# Supplementary Information

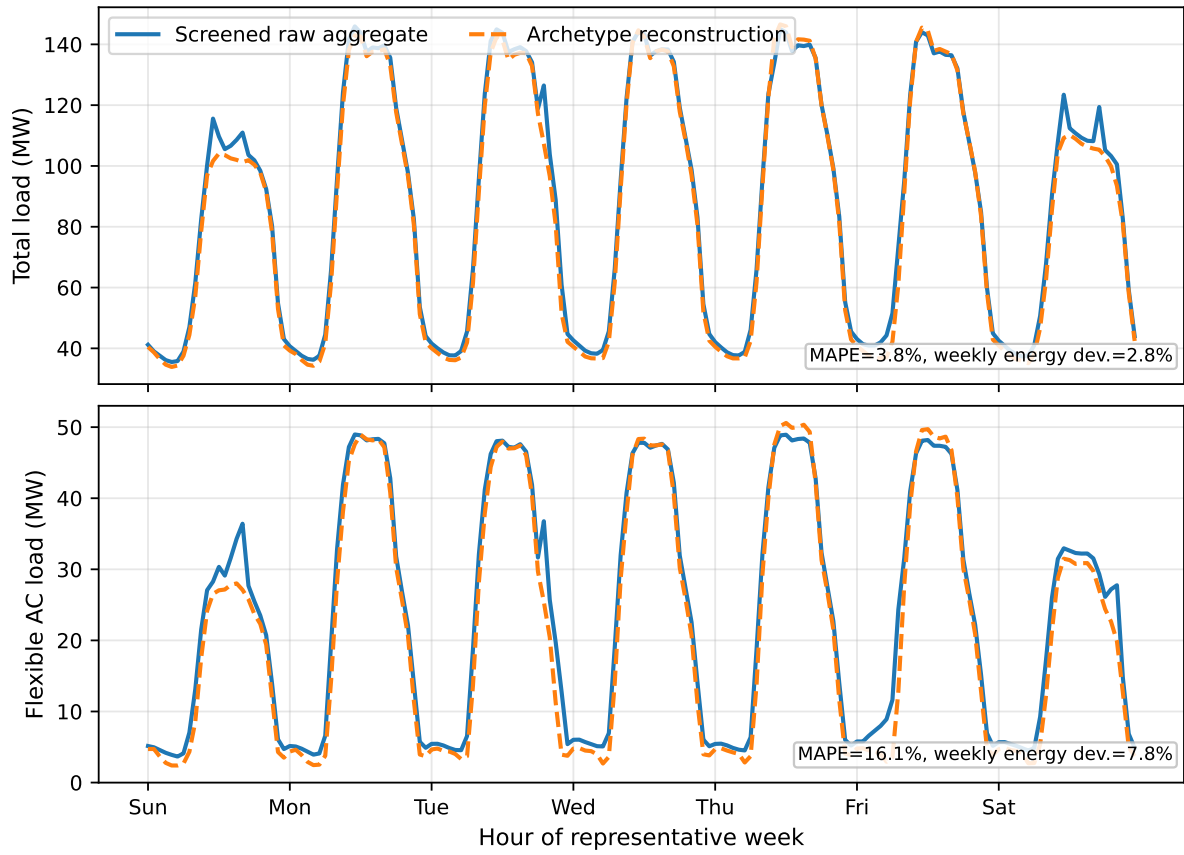
## Valuing urban building flexibility portfolios under carbon-constrained electricity dispatch: A Shenzhen case study

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### Supplementary figures



Supplementary Figure S1: A-type sensitivity at  $\rho = 0.60$  and  $\delta = 0.60\%$ . (a) Matched-reference subsystem operating-cost saving. (b) Shifted energy, defined as  $\frac{1}{2} \sum_{k,t} (s_{k,t}^+ + s_{k,t}^-) \Delta t$ .



Supplementary Figure S2: Preprocessing consistency check comparing the three-group dispatch input with an independently reconstructed aggregate produced using an additional local-median spike filter. The differences reflect this additional filtering step.

## Supplementary method: clustering diagnostic

The clustering diagnostic uses the 145 building records with matched floor-area metadata. For each building, the first 8,736 observations form 52 complete 168-hour blocks. The mean profile over those blocks is divided by floor area, vectorized across five load channels, and standardized feature by feature. Silhouette scores use `KMeans(random_state=0, n_init=10)` for  $K = 2, \dots, 8$ ; the final  $K = 5$  fit uses `n_init=20`. Two singleton groups correspond to abnormal meter profiles and are removed before the three retained groups are reconstructed with weekly medians. The clustering script is available from the corresponding author upon reasonable request and reproduces this diagnostic when authorized source records are available.

## Supplementary tables

Supplementary Table S1: Summary of building archetypes for the 143-building screened sample.

| Cluster | Number of buildings | Used area (m <sup>2</sup> ) | Area share (%) |
|---------|---------------------|-----------------------------|----------------|
| 0       | 96                  | 5,027,363.73                | 76.95          |
| 1       | 15                  | 293,892.45                  | 4.50           |
| 2       | 32                  | 1,212,243.09                | 18.55          |

Supplementary Table S2: Sensitivity to offer-based generator emission factors at  $\rho = 0.60$  and  $\delta = 0.60\%$ . The A-type cases use a uniform shifting cost of 80 RMB/MWh and bounds  $(\alpha^{down}, \alpha^{up}) = (0.2, 0.1)$ .

| Case         | Coal/gas factors<br>(tCO <sub>2</sub> /MWh) | Base emissions<br>(ktCO <sub>2</sub> ) | Rigid budget dual<br>(RMB/tCO <sub>2</sub> ) | A saving<br>(M RMB) | B budget dual<br>(RMB/tCO <sub>2</sub> ) | B saving<br>(M RMB) | B reduction<br>(MWh) |
|--------------|---------------------------------------------|----------------------------------------|----------------------------------------------|---------------------|------------------------------------------|---------------------|----------------------|
| Low factors  | 0.70/0.35                                   | 425.49                                 | 314.14                                       | 0.410               | 113.54                                   | 1.108               | 2306                 |
| Base factors | 0.90/0.40                                   | 546.36                                 | 242.51                                       | 0.410               | 88.41                                    | 1.102               | 2283                 |
| High factors | 1.00/0.55                                   | 608.54                                 | 221.16                                       | 0.410               | 80.09                                    | 1.112               | 2320                 |

Supplementary Table S3: Aggregation-resolution and air-conditioning-envelope checks at  $\rho = 0.60$  and  $\delta = 0.60\%$ . Resolution cases use a uniform shifting cost of 80 RMB/MWh, A-type bounds (0.2, 0.1), and B-type bounds (0.3, 0.2) with  $\eta = 2\%$  and  $c^{red} = 200$  RMB/MWh.

| Case               | A saving<br>(M RMB/week) | A shifted energy<br>(MWh/week) | B saving<br>(M RMB/week) | B budget dual<br>(RMB/tCO <sub>2</sub> ) | B net reduction<br>(MWh/week) |
|--------------------|--------------------------|--------------------------------|--------------------------|------------------------------------------|-------------------------------|
| $K = 1$            | 0.410                    | 836.74                         | 1.100                    | 88.41                                    | 2282                          |
| $K = 3$            | 0.410                    | 836.74                         | 1.102                    | 88.41                                    | 2283                          |
| $K = 143$          | 0.397                    | 814.47                         | 1.087                    | 88.41                                    | 2273                          |
| AC envelope $-5\%$ | 0.389                    | 794.90                         | 1.055                    | 93.08                                    | 2213                          |
| AC envelope base   | 0.410                    | 836.74                         | 1.102                    | 88.41                                    | 2283                          |
| AC envelope $+5\%$ | 0.430                    | 878.57                         | 1.149                    | 87.88                                    | 2287                          |

Relative to  $K = 143$ , The  $K = 3$  errors are 0.009% in A-type total objective, 3.28% in A-type saving, and 2.73% in shifted energy. The corresponding B-type errors are 0.011% in total objective, 1.41% in saving, and 0.43% in net reduction. The budget duals are unchanged. The 16.07% preprocessing MAPE in Supplementary Table S4 includes temporal-shape and level changes from an alternative filter. the  $\pm 5\%$  rows above are local uniform-scaling tests.

Supplementary Table S4: Preprocessing consistency metrics used in Supplementary Fig. S2.

| Profile          | MAPE (%) | Energy deviation (%) | P95 deviation (%) |
|------------------|----------|----------------------|-------------------|
| Total load       | 3.81     | 2.75                 | 5.72              |
| Flexible AC load | 16.07    | 7.81                 | 11.89             |

Supplementary Table S5: Finite-difference validation of the accounted-emissions-budget dual. Broad secants cross multiple linear-program bases. The local  $\pm 1$  tCO<sub>2</sub> perturbation remains in one basis and reproduces the dual to six decimal places.

| Cap interval                   | Secant/central difference<br>(RMB/tCO <sub>2</sub> ) | Left dual<br>(RMB/tCO <sub>2</sub> ) | Right dual<br>(RMB/tCO <sub>2</sub> ) |
|--------------------------------|------------------------------------------------------|--------------------------------------|---------------------------------------|
| 0.05–0.10                      | 25.9                                                 | 24.58                                | 27.79                                 |
| 0.10–0.15                      | 35.7                                                 | 27.79                                | 39.79                                 |
| 0.15–0.20                      | 40.7                                                 | 39.79                                | 52.53                                 |
| 0.20–0.30                      | 64.8                                                 | 52.53                                | 80.50                                 |
| 0.30–0.40                      | 110.9                                                | 80.50                                | 140.12                                |
| 0.40–0.50                      | 212.7                                                | 140.12                               | 231.24                                |
| 0.50–0.60                      | 238.9                                                | 231.24                               | 242.51                                |
| 0.60% $\pm 1$ tCO <sub>2</sub> | 242.508866                                           | 242.508866                           | 242.508866                            |

Supplementary Table S6: Silhouette diagnostic for the 145 metadata-matched building records.

| $K$ | Silhouette score | Selected |
|-----|------------------|----------|
| 2   | 0.471            | No       |
| 3   | 0.444            | No       |
| 4   | 0.439            | No       |
| 5   | 0.487            | Yes      |
| 6   | 0.425            | No       |
| 7   | 0.410            | No       |
| 8   | 0.401            | No       |

Supplementary Table S7: Hours at the subsystem import ceiling, using a numerical tolerance of  $10^{-5}$  MW.

| Scenario                                  | Binding hours (of 168) |
|-------------------------------------------|------------------------|
| Base                                      | 109                    |
| Rigid demand, $\delta = 0.60\%$           | 137                    |
| A-type, $\rho = 0.60$ , $\delta = 0.60\%$ | 138                    |
| A-type, $\rho = 0.60$ , no emissions cap  | 109                    |

Supplementary Table S8: Summary of the 168-hour boundary signals. The Pearson correlation between import price and the provincial average operational emissions proxy is 0.196.

| Signal                                  | Minimum | Mean   | Maximum |
|-----------------------------------------|---------|--------|---------|
| Import price (RMB/MWh)                  | 134.21  | 184.06 | 881.61  |
| Emissions proxy (tCO <sub>2</sub> /MWh) | 0.6703  | 0.7130 | 0.7373  |