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Sustainable battery recycling through spatial and technological alignment

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Supplementary Note

Note S1. Cities information

This study covers 364 mainland Chinese cities, including (full list in Table S1): Provincial-level municipalities (4), Prefecture-level cities (293), Administrative regions (7), Autonomous prefectures (30), Leagues (3), County-level cities directly governed by provinces (27).

* Data from Taiwan (China), Hong Kong (China), Macau (China), and the cities of Kekdala, Kunyu, Huyanghe, Xinxing, and Baiyang in the Xinjiang Uygur Autonomous Region were excluded due to data availability limitations. Administrative codes follow *Code of administrative divisions above county level in the People's Republic of China in 2022*[1].

Note S2. Differences between passenger electric vehicles and electric commercial vehicles

Electric passenger vehicles are primarily used for daily personal or household travel, such as commuting, shopping, and short trips. Their design emphasizes comfort, driving experience, and smart features (e.g., autonomous driving assistance, intelligent cabins). The target audience is general consumers, who particularly value brand reputation, driving range, and charging convenience. These vehicles feature relatively high battery energy density, with durability tailored for daily use, typically designed for 1,500-2,000 charge-discharge cycles. Daily usage involves low mileage, with charging relying mainly on home slow charging or public fast charging. Policy support in China includes purchase subsidies, exemption from vehicle purchase taxes, and free or prioritized electric vehicle license plates to promote adoption.

Electric commercial vehicles serve commercial transportation and public services, including urban logistics delivery, public transit, sanitation operations, and specialized engineering vehicles (e.g., refrigerated trucks, dumping trucks). The target users are enterprises, government agencies, or fleet operators. Their batteries have slightly lower energy density but larger capacity to support heavy loads and long-range needs. Durability requirements are stringent, requiring tolerance for high-frequency charge-discharge cycles (>3,000 cycles) and enhanced thermal management systems for intensive operations[2]. Usage frequency is significantly higher than passenger vehicles, with daily mileage exceeding 200 km, relying on centralized fast-charging stations or battery-swapping networks. Policy support is stronger and more mandatory; for example, China mandates that no less than 80% of new or updated public-sector vehicles (e.g., buses, taxis, urban logistics trucks, light-duty sanitation vehicles) in key regions must be electric vehicles[3]。

Note S3. Data source

The compulsory traffic accident liability insurance data for electric vehicles used in this study were obtained from official government records. City-level characteristic data, including Gross Domestic Product (GDP), urbanization rate, population size, Baidu Index scores, and government subsidy amounts[4] were primarily obtained from the China Statistical Yearbook, official municipal statistical bureau reports, and publicly available government policy documents. Baidu Index[5] data (Note S4) was collected using Python web scraping techniques, while information regarding urban recycling capacities and technical specifications was sourced from the China Proposed and Under-Construction Projects Database[6].

Metal recovery rates for certified enterprises were derived from the "*Technical Specifications for Comprehensive Utilization of Retired Power Batteries from New Energy Vehicles (2024 Edition)*"[7], which mandates minimum recovery rates of 90% for lithium and 98% for nickel, cobalt, and manganese during smelting processes. Future urban GDP projections were determined through integration of economic expert forecasts, regional development plans, and macroeconomic trend analyses. Urban population projections were referenced from YuWa Population Research[8]. Electric vehicle promotion subsidies were projected to decrease annually by 50% from the 2024 baseline[9], reflecting current policy phase-out trends.

Note S4. Baidu Index description

Baidu Index is a publicly available analytics platform provided by Baidu, Inc., China's market-leading search engine. Search query frequencies and trends for specific keywords are reported, serving as a proxy indicator of public attention and interest across topics. Baidu Index provides daily, weekly, monthly, or annual data, which can be disaggregated by region (e.g., city level), device type (e.g., mobile or PC), and demographic attributes. Given Baidu's extensive user base, Baidu Index is widely regarded as a reliable indicator of real-time public sentiment and behavioral intentions in China[10,11].

The selection of Baidu Index as a predictive feature in this study is grounded in consumer behavior theory, which posits that consumers typically engage in information-seeking activities before making purchase decisions. In the digital era, search engines have become a primary tool for gathering product information, comparing alternatives, and evaluating brands. Thus, fluctuations in search volume for specific keywords ("Electric vehicles") can signal changes in consumer demand, serving as a leading indicator for future sales. Specifically, in the context of electric vehicles, potential buyers often search for information on models, pricing, government policies, and technological features before visiting dealerships or making purchases. Baidu Index captures these pre-purchase behaviors, allowing researchers to quantify urban-level interest in electric vehicles.

To incorporate Baidu Index into our predictive model, we collected daily search data for the keyword "Electric vehicles" across all prefecture-level cities in China from January 1, 2016, to December 31, 2024. The data acquisition process involved the following steps:

- **Crawling Method**: We developed a Python-based web crawler to automatically extract daily Baidu Index data from the official Baidu Index platform (https://index.baidu.com)[5]. The crawler simulated user requests to retrieve structured data, including city-specific search indices for the target keyword.

- **Data Scope**: The dataset covers cities in China (Note S1), ensuring comprehensive geographic representation. For each city, we obtained the daily Baidu Index value for "Electric vehicles", which reflects the relative search volume normalized by Baidu's algorithms.

- **Temporal Range**: The data span nine years (2016–2024), capturing long-term trends and seasonal variations in public attention toward EVs. This period includes key policy changes (e.g., subsidy adjustments) and market shifts, enhancing the model's robustness.

- **Data Aggregation**: Daily data were aggregated into monthly averages to align with the monthly sales data of EVs at the city level. This aggregation reduces noise and facilitates integration with other economic variables in the predictive model.

Note S5. Capacity information for lithium-ion battery recycling projects

Capacity information is obtained from publicly available project listings on the China Construction Project Network (http://www.bhi.com.cn/).The dataset has a cutoff date of December 2024. City- and province-level capacities compiled for 2020-2030 are based on observed announcements rather than forecasts. Data for 2020-2024 derive from projects that have commenced, whereas data for 2025-2030 aggregate planned start dates from announced projects. Captured attributes include project start date, equipment specifications, nameplate capacity, and battery types processed. Accordingly, the capacity dataset represents best-available information rather than definitive totals.

Note S6. Machine learning framework and hyperparameter optimization

We assemble a monthly panel covering 364 prefecture-level cities in China from 2016 to 2030. The monthly cadence explicitly captures seasonality and cyclical replacement dynamics in EV diffusion, mitigating aggregation bias relative to annual data.

- To accommodate substantial cross-city heterogeneity, we embed cities using training-period ($\leqslant$ 2023) indicators (population, GDP, urbanization rate, search intensity, and subsidy amounts) and perform clustering. The optimal number of clusters K is selected by a composite criterion combining the silhouette score, Calinski–Harabasz index, and Davies-Bouldin index.

- Within each cluster, we compare the same suite of models: Support Vector Machines (SVM) (Note S7), Random Forests (Note S8), XGBoost (Note S9), Artificial Neural Networks (Note S10), and two lightweight ensembles (Stacking and a two-model blend, "BlendTop2"). Model selection prioritizes test-set R^2 (year 2024) with normalized mean squared error (NMSE) as a secondary criterion, and we record the winning model together with its tuned hyperparameters or blending weights. Cluster-specific modeling reduces geographic heterogeneity while enhancing interpretability.

- Time information is encoded with sine/cosine seasonality, and target construction relies strictly on historically available lags and seasonal differences (e.g., $y_{t-1} - y_{t-13}$ and rolling mean contrasts). Hyperparameters are tuned with TimeSeriesSplit and RandomizedSearchCV; all scaling, PCA, and target transformations are fit exclusively within the training folds via pipelines to prevent leakage.

- After evaluation is finalized (with no further model adjustments), we refit the chosen models on the full historical sample for 2016-2024 to improve downstream utility, and then generate month-by-month forecasts for 2025-2030.

All reported test metrics are computed on the held-out 2024 set; the extrapolation phase does not enter model selection or tuning. Data preprocessing steps, search spaces, and figure generation are fully documented in code to facilitate replication.

Note S7. Support Vector Machines

Support Vector Machine (SVM) algorithm is employed to model potentially complex, non-linear relationships between the economic indicators and future automobile quantities. Unlike traditional regression models that aim to minimize the sum of squared errors, SVM is based on the structural risk minimization principle[12]. This principle seeks to minimize an upper bound on the generalization error, making the model more robust to overfitting, particularly in contexts with finite sample sizes. The core innovation of SVM is its use of an ϵ-insensitive loss function. This function defines a symmetrical tube of radius ϵ around the regression function. Errors on training data points that fall within this tube are completely ignored. For points outside the tube, the error is measured as their vertical distance to the edge of the tube. This approach imparts robustness by focusing the model on the overall trend rather than fitting to minor fluctuations or noise within the ϵ margin.

Note S8. Random forest

The random forest classifier was implemented using the Scikit-learn library[13]. This ensemble method integrates multiple decision trees through a structured construction process[14]: 1) Bootstrap sampling is first performed to generate distinct training subsets through random sampling with replacement. 2)

Feature subspace randomization occurs at each node, where a predefined number of features are randomly selected for split evaluation. 3) Greedy split optimization is then executed within the constrained feature subspace to maximize information gain. 4) Recursive partitioning continues until terminal nodes satisfy predefined stopping criteria.

Note S9. XGBoost model

A distributed gradient boosting library optimized through a gradient-enhanced framework, which builds the final model by iteratively optimizing the objective function over multiple rounds:

$$\mathcal{L}^{(t)} = \sum_{i=1}^{n} l\left(y_i, \hat{y}_i^{(t-1)} + f_t(x_i)\right) + \Omega\left(f_t\right) \tag{1}$$

where, $\mathcal{L}^{(t)}$ is the value of the objective function at the t-th iteration. n is the number of samples, i is the index of the sample. y_i is the true label value of the i-th sample. l is the loss function. $\hat{y}_i^{(t-1)}$ is the predicted value for the i-th sample from the $(t-1)$-th iteration. $f_t(x_i)$ is the prediction value contributed by the newly added tree for the i-th sample.

Note S10. Artificial neural network model

Artificial Neural Networks (ANNs) are universal function approximators built by stacking linear mappings and nonlinear activations[15]. The most common architecture is a multilayer perceptron, which comprises an input layer, one or more hidden layers, and an output layer. Model parameters are learned by minimizing a loss function with first-order, gradient-based optimizers. Assuming the network has two hidden layers, the output of each layer can be represented as follows:

$$z^{[l]} = W^{[l]} a^{[l-1]} + b^{[l]} \tag{2}$$

$$a^{[l]} = g\left(z^{[l]}\right) \tag{3}$$

where $z^{[l]}$ is the weighted input of the l layer, $W^{[l]}$ and $b^{[l]}$ denote the weight matrix and bias vector, respectively. These parameters are iteratively updated through the optimization algorithm to minimize the loss function. Here, g represents the activation function, and $a^{[l]}$ is the activation output of the l layer.

Note S11. Best-performing model configurations by city cluster

Abbreviations: CEV = commercial electric vehicles; PEV = passenger electric vehicles; XGB = XGBoost; ANN = artificial neural network; SVM = support vector machine.

Blending rule: BlendTop2 denotes a weighted linear ensemble of two base models; final prediction = weight1 × model1 + weight2 × model2.

- **CEV (by city cluster)**
  - **Cluster 0 — Best model: XGB**

"model": "XGB",
"params": {
  "subsample": 0.8,
  "reg_lambda": 1.0,
  "reg_alpha": 0.0,
  "n_estimators": 300,
  "min_child_weight": 5,
  "max_depth": 4,
  "learning_rate": 0.05,
  "gamma": 0,
  "colsample_bytree": 1.0}

  - **Cluster 1 — Best model: BlendTop2 (XGB + ANN)**

"model": "BlendTop2",
"weight1": 0.6,
"weight2": 0.4,
"model1": "XGB",
"model1_params": {
  "subsample": 0.9,

```
    "reg_lambda": 1.0,
    "reg_alpha": 0.1,
    "n_estimators": 300,
    "min_child_weight": 1,
    "max_depth": 5,
    "learning_rate": 0.05,
    "gamma": 0,
    "colsample_bytree": 1.0
  },
  "model2": "ANN",
  "model2_params": {
    "learning_rate_init": 0.01,
    "hidden_layer_sizes": [64, 32],
    "batch_size": "auto",
    "alpha": 0.003
  }
```

- **Cluster 2 — Best model: XGB**

```
  "model": "XGB",
  "params": {
    "subsample": 0.9,
    "reg_lambda": 1.0,
    "reg_alpha": 0.1,
    "n_estimators": 300,
    "min_child_weight": 1,
    "max_depth": 5,
    "learning_rate": 0.05,
    "gamma": 0,
```

"colsample_bytree": 1.0

}

- **PEV (by city cluster)**
  - **Cluster 0 — Best model: BlendTop2 (ANN + SVM)**

```
"model": "BlendTop2",
"blend_weight": 0.6,
"ANN_params": {
  "learning_rate_init": 0.003,
  "hidden_layer_sizes": [150, 100, 50],
  "batch_size": 32,
  "alpha": 0.0005
},
"SVM_params": {
  "kernel": "rbf",
  "gamma": 0.0001,
  "epsilon": 0.05,
  "C": 3
}
```

  - **Cluster 1 — Best model: ANN**

```
"model": "ANN",
"params": {
  "learning_rate_init": 0.001,
  "hidden_layer_sizes": [150, 75],
  "batch_size": 64,
  "alpha": 0.0001
}
```

- **Cluster 2 — Best model: ANN**

```
"model": "ANN",
"params": {
  "learning_rate_init": 0.01,
  "hidden_layer_sizes": [150, 75],
  "batch_size": 32,
  "alpha": 0.01
}
```

Note S12. Weibull specifies life distribution

The Weibull distribution encompasses various distribution forms through its shape parameter k_m, with k_m = 3.5 producing an approximately normal distribution[16]. The scale parameter λ_m governs the average service life of batteries in vehicle model m. The Weibull life distributions for 24 battery types are illustrated in Figure S6.

Commercial electric vehicles experience accelerated battery degradation due to intensive operational demands, including extended daily utilization periods and frequent charge-discharge cycles. In contrast, passenger electric vehicles exhibit comparatively lower battery stress factors, with reduced daily mileage and charge-discharge frequency relative to commercial counterparts. This differential usage pattern results in longer operational lifespans for passenger vehicle batteries. Battery cycling data, where applicable, were collected using a NEWARE battery testing system (model: CE-4008Q-5V15A-S1).

Note S13. Standard deviation ellipse

The standard deviation ellipse (SDE) is used to measure the spatial statistical distribution characteristics of geographical elements. In this study, the SDE method was used to characterise the spatial distribution of retired power batteries using the centre of gravity, long axis, short axis and azimuth angle of the spatial distribution ellipse as the basic parameters. First, the centre of the ellipse is determined. The centre used in the directional distribution tool is calculated as the arithmetic mean centre, using the following formula:

$$SDE_x = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{X})^2}{n}}$$

$$SDE_y = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \bar{Y})^2}{n}}$$

Where x_i and y_i are the spatial coordinates of each feature, $\bar{X}$ and $\bar{Y}$ represent the arithmetic mean centre. SDE_x and SDE_y are then calculated to determine the centre of the resulting ellipse. Next, the direction (or orientation) of the ellipse is determined with respect to the x-axis. The angle is measured clockwise from the north direction (12 o'clock position), which is defined as 0°, using the following formula:

$$\tan\theta = \frac{A + B}{C}$$

$$A = \left(\sum_{i=1}^{n} \tilde{x}_i^2 - \sum_{i=1}^{n} \tilde{y}_i^2\right)$$

$$B = \sqrt{\left(\sum_{i=1}^{n} \tilde{x}_i^2 - \sum_{i=1}^{n} \tilde{y}_i^2\right)^2 + 4\left(\sum_{i=1}^{n} \tilde{x}_i\tilde{y}_i\right)^2}$$

$$C = 2\sum_{i=1}^{n} \tilde{x}_i\tilde{y}_i$$

$\tilde{x}_i$ and $\tilde{y}_i$ are the coordinate deviations of each city to the mean center of gravity; θ is the azimuth of the ellipse; θ is the azimuth of the ellipse. Finally, the lengths of the X and Y axes are determined and plotted on the map using ArcGIS 10.5 software.

$$\sigma_x = \sqrt{2}\sqrt{\frac{\sum_{i=1}^{n} (\tilde{x}_i \cos\theta - \tilde{y}_i \sin\theta)^2}{n}}$$

$$\sigma_y = \sqrt{2}\sqrt{\frac{\sum_{i=1}^{n} (\tilde{x}_i \sin\theta + \tilde{y}_i \cos\theta)^2}{n}}$$

$$S = \pi\sigma_x\sigma_y$$

σ_x and σ_y represent the standard deviations of the long axis and short axis of the ellipse; and S represents the area of the ellipse, respectively.

The SDE gravity centres and their changing trajectories represent the relative location of geographically dispersed elements and the spatial development directions of those elements in space. The long axis represents the element's distribution direction, while the short axis represents its distribution range. The azimuth angle reflects the predominant distribution direction of an element[17,18].

Note S14. Assumptions for estimating the proportion of recycling processes

To address provincial data gaps in recycling technology distribution, scientifically grounded estimations were implemented through the following assumptions to ensure methodological transparency. Verified enterprise data included minimum requirements for power battery recyclers: USD 1.43 million registered capital, USD 0.71 million paid-in capital, and $\geqslant$5,000 t yr^{-1} operational capacity[19]. Provincial recycling capacities (2020-2030) were obtained from the China Project Construction Network, encompassing both operational and planned facilities. Formal/informal enterprise ratios were determined using industrial registration records[20] and the Whitelist[21], while informal sector capacities utilizing outdated technologies required indirect modeling due to non-disclosure of operational data.

Three core assumptions guided the estimation framework:

- Informal enterprises were allocated 40% of national recycling capacity in baseline scenarios[22], reflecting their competitive advantage in cost-efficient (though technologically inferior) operations as documented in the *China Power Battery Recycling Industry White Paper (2024)*.
- Enterprise quantity ratios were considered proportional to capacity distribution.
- Outdated technologies (e.g., open-air incineration) were exclusively attributed to informal enterprises, consistent with Ministry of Industry and Information Technology of China mandates requiring whitelisted facilities to employ hydrometallurgical or pyro-hydrometallurgical processes.
- Outdated hydrometallurgical and pyrometallurgical processes are equally distributed across provincial-level administrative regions, each accounting for 50% of obsolete recycling technologies.

Note S15. Sensitivity analysis

We analysed the uncertainties in the predictive outcomes of this study. Initially, a sensitivity analysis was conducted to identify the most sensitive parameters in the computational model, which included annual electric vehicle sales, battery lifespan, and battery energy density. Each parameter was then varied by ±10%, and the altered metrics were compared with the default metrics. Through this approach, potential errors within these parameters were identified, followed by discussions on any possible overestimations, underestimations, and model uncertainties.

Note S16. Stacking ensemble model

In machine learning, stacking ensemble methods are recognised as robust frameworks for enhancing predictive performance by hierarchically combining base models and a meta-model. The core principle of stacking lies in leveraging the predictions of diverse base models as input features for a meta-model, thereby synthesising their complementary strengths while reducing bias and variance inherent in single-model approaches[23]. This study employs a stacking architecture integrating random forest (base model) and linear regression (meta-model). The random forest, serving as the base model, excels at capturing complex non-linear relationships and high-dimensional feature interactions, with its ensemble of decision trees mitigating overfitting risks through majority voting—a critical advantage for noisy or incomplete datasets[24]. The linear regression meta-model provides a parsimonious linear weighting mechanism to consolidate base predictions, distilling global trends while offering interpretability via explicit coefficient interpretation of feature importance[25]. This hybrid design preserves the random forest's sensitivity to local data patterns while imposing linear regression's global regularisation, achieving an optimised bias-variance trade-off[26]. Cross-validation demonstrates superior stability in predictive accuracy, particularly under imbalanced data distributions or multicollinearity.

Note S17. Simulation description of cross-regional transportation of EOL batteries

Let $d_{i,j}^{\mathrm{road}}$ be the shortest road distance (km) between origin city i and target city j returned by the

Amap API. We define the effective logistics distance as $\hat{d}_{i,j} = 1.3 \times d_{i,j}^{\text{road}}, \hat{d}_{i,i} = 10$ km (same-city floor).

We simulate three plausible cross-regional policies for **formal** recyclers (licensed, inter-provincial transport permitted), keeping **informal** treatment local (within province) due to legal and capacity constraints:

- **Local-radius (300 km)**: origin city i may ship to any capacity city j located in a province p whose nearest entry city lies within 300 km of i.
- **Urban-cluster collaboration**: i may ship to any capacity city inside the same national urban cluster as i.
- **Adjacent-province**: i may ship to any capacity city in its home province or any administratively adjacent province.

Formally, let $\mathcal{C}_s(i)$ be the candidate provinces for scenario $s \in$ {radius300,cluster,neighbor}. The candidate target cities for year t are $\mathcal{J}_{i,t}^{(s)} = \{ j: \text{prov}(j) \in \mathcal{C}_s(i), \text{cap}_{j,t} > 0 \}$.

Formal vs. informal split and K-calibration

At city-year (i, t), predicted EOL mass is $E_{i,t}$. We set a national target formal share τ_t (2020→0.25, 2021→0.30, 2022→0.35, 2023→0.40, 2024→0.45)[22], then calibrate a factor K_t so that the achieved formal service rate under baseline matches τ_t at national level. Denote the served formal mass by $S_t^{\text{form}}(K_t)$. We solve $K_t^{\star} = \arg\min_{K_t \in [0,1]} \left| \frac{S_t^{\text{form}}(K_t)}{\sum_i E_{i,t}} - \tau_t \right|$. City-level formal supply is $\min\{K_t^{\star}\tau_t \cdot E_{i,t}, E_{i,t}\}$; the informal remainder is $R_{i,t}^{\text{inf}} = E_{i,t} - \text{formal}_{i,t}$.

Distance-aware matching to capacity cities

For a scenario s, year t, and origin city i, we allocate its formal supply to target cities $j \in \mathcal{J}_{i,t}^{(s)}$ **prioritizing** (1) in-province destinations, then (2) ascending $\hat{d}_{i,j}$, subject to residual capacity $\text{cap}_{j,t}^{\text{left}}$. Let $x_{i,j,t}$ be the assigned tons. The formal **ton-kilometres** are $\text{TKM}_t^{\text{form}} = \sum_i \sum_j x_{i,j,t} \, \hat{d}_{i,j}$.

Informal flows are assumed intra-provincial. For province p, we pre-compute an average inter-city distance $\bar{d}_p$ (mean of finite $\hat{d}_{i,j}$ among cities in p; if single-city or missing, $\bar{d}_p = 10$ km).

Informal ton-kilometres are $\mathrm{TKM}_t^{\mathrm{inf}} = \sum_i R_{i,t}^{\mathrm{inf}} \bar{d}_{\mathrm{prov}(i)}$. We split informal tons between **micro** and **medium** workshops by capacity-weighted shares using enterprise counts per province-year.

We report, by scenario s and year t: (i) province-level **receiving** metrics (served tons, inbound TKM, average haul, utilization), (ii) province-level **origin** balances (generated, formal, informal, informal-TKM), and (iii) city-level formal/informal split with **both** formal-TKM (from flows) and informal-TKM. National checks ensure $\sum_i$ formal+ $\sum_i$ informal $= \sum_i E_{i,t}$ (no unrecycled remainder).

Note S18. City-level process shares

This study computes recycling process shares (technology portfolios) for each city i (and, by aggregation, its corresponding province p) in year t by coupling city-level EOL battery flows and chemistry composition, the formal–informal split, the size structure of informal enterprises, and process-mapping rules that are aligned with industry capacity and LCA definitions. The data include: (1) city-level EOL totals and the LFP/NCM composition; (2) city-level formal and informal recycling volumes generated by the cross-regional transport simulation; (3) provincial counts of medium- and micro-scale informal enterprises, used to infer the size shares within the informal sector; (4) eight recycling process routes consistent with the LCA unit table; and (5) city-level capacity data for formal enterprises. The computation proceeds in four steps: **Step 1 (chemistry split):** partition each city's EOL total into LFP and NCM masses. **Step 2 (channel split):** divide each chemistry into formal and informal channels, and further split the informal mass into "medium/micro" according to the enterprise counts. **Step 3 (process mapping):** map the quantities for formal, informal–medium, and informal–micro channels to specific processes (e.g., formal → low-emission; informal–medium LFP → medium-emission; informal–micro → two low-emission routes on a 50/50 basis), then sum by process to obtain the city–chemistry–process mass matrix. **Step 4 (share formation and fallback):** normalize within each chemistry to obtain city-level process shares; if a given city–chemistry cell lacks informative mass, fall back to the province-level process shares obtained by aggregating all cities in that province using the same method. This procedure yields a complete and auditable set of city-level technology portfolios, providing the foundation for subsequent integration with cross-regional transport scenarios and LCA impact factors.

Step1: chemistry split

For each city i, year t, chemistry $b \in \{\text{LFP, NCM}\}$:

$$M_{i,b,t} = \theta_{i,b,t} M_{i,t} .$$

Step2: channel split

Based on this study's city-by-year forecasts of LFP and NCM retirements, flows are split into formal and informal channels according to the observed formal-share parameter:

$$M_{i,b,t}^{\text{formal}} = \alpha_{i,t} M_{i,b,t}, M_{i,b,t}^{\text{inf}} = (1 - \alpha_{i,t}) M_{i,b,t} .$$

Further divide informal mass by provincial size structure of province $p = \text{prov}(i)$:

$$M_{i,b,t}^{\text{inf,med}} = \pi_{p,t}^{\text{med}} M_{i,b,t}^{\text{inf}}, M_{i,b,t}^{\text{inf,mic}} = \pi_{p,t}^{\text{mic}} M_{i,b,t}^{\text{inf}}$$

Where, $M_{i,t}$ is total EOL volume (t) in city i and year t; $\theta_{i,b,t}$ denotes chemistry composition shares (LFP/NCM) at city i, year t; $F_{i,t}$, $I_{i,t}$ are formal and informal collection volumes (t) inferred for city i, year t; $\alpha_{i,t} = \frac{F_{i,t}}{F_{i,t}+I_{i,t}}$ is formal share at city i, year t; $N_{p,t}^{\text{med}}$ denotes medium-sized enterprises for provincial p counts by year t, $N_{p,t}^{\text{mic}}$ denotes micro-sized enterprises for provincial p counts by year t. $\pi_{p,t}^{\text{med}} = \frac{N_{p,t}^{\text{med}}}{N_{p,t}^{\text{med}}+N_{p,t}^{\text{mic}}}, \pi_{p,t}^{\text{mic}} = 1 - \pi_{p,t}^{\text{med}}$ denotes provincial size shares.

Step 3: process mapping

We map each channel/size to process routes p as follows (baseline assumptions consistent with practice and LCA definitions):

- **Formal**
    - LFP: $M_{i,\text{LFP},t}^{\text{formal}} \rightarrow$ low emission hydrometallurgy for LFP
    - NCM: $M_{i,\text{NCM},t}^{\text{formal}} \rightarrow$ low emission hydrometallurgy for NCM

- **Informal–medium**
  - LFP: $M_{i,\mathrm{LFP},t}^{\mathrm{inf,med}} \rightarrow$ medium emission pyrometallurgy for LFP
  - NCM: $M_{i,\mathrm{NCM},t}^{\mathrm{inf,med}} \rightarrow$ medium emission hydrometallurgy for NCM
- **Informal–micro**
  - LFP: $M_{i,\mathrm{LFP},t}^{\mathrm{inf,mic}} \rightarrow$ high emission hydrometallurgy for LFP
  - NCM: split equally between hydrometallurgy and pyrometallurgy:$\frac{1}{2} M_{i,\mathrm{NCM},t}^{\mathrm{inf,mic}} \rightarrow$ high emission hydrometallurgy for NCM, $\frac{1}{2} M_{i,\mathrm{NCM},t}^{\mathrm{inf,mic}} \rightarrow$ high emission pyrometallurgy for NCM.

This yields **city–chemistry–process** masses $m_{i,b,p,t}$ by summing contributions from applicable channels/sizes:

$$m_{i,b,p,t} = \begin{cases} M_{i,\mathrm{LFP},t}^{\mathrm{formal}}, & b = \mathrm{LFP}, p = \text{low emission hydrometallurgy LFP} \\ M_{i,\mathrm{NCM},t}^{\mathrm{formal}}, & b = \mathrm{NCM}, p = \text{low emission hydrometallurgy NCM} \\ M_{i,\mathrm{LFP},t}^{\mathrm{inf,med}}, & b = \mathrm{LFP}, p = \text{medium emission pyrometallurgy LFP} \\ M_{i,\mathrm{NCM},t}^{\mathrm{inf,med}}, & b = \mathrm{NCM}, p = \text{medium emission hydrometallurgy NCM} \\ 0.5 M_{i,\mathrm{NCM},t}^{\mathrm{inf,mic}}, & b = \mathrm{NCM}, p \in \{\text{high emission hydrometallurgy /pyrometallurgy NCM}\} \\ M_{i,\mathrm{LFP},t}^{\mathrm{inf,}}\mathrm{mic}, & b = \mathrm{LFP}, p = \text{high} - \text{emission hydrometallurgy for LFP} \\ 0, & \text{otherwise}. \end{cases}$$

Step 4: share formation and fallback

Define the **city-level process share** $s_{i,b,p,t}$ for chemistry b over its compatible process set $\mathcal{P}_b$:

$$s_{i,b,p,t} = \begin{cases} \dfrac{m_{i,b,p,t}}{\sum_{p' \in \mathcal{P}_b} m_{i,b,p',t}}, & \text{if } \sum\limits_{p'} m_{i,b,p',t} > 0 \\ \tilde{s}_{p(i),b,p,t}^{\mathrm{prov}}, & \text{otherwise} \end{cases}$$

where $p(i)$ is the province of city *i*. The **province-level fallback share** $\tilde{s}_{p,b,p,t}^{\mathrm{prov}}$ is constructed analogously by aggregating masses across cities within province *p*:

$$\tilde{s}^{\text{prov}}_{p,b,p,t} = \frac{\sum_{i\in p} m_{i,b,p,t}}{\sum_{i\in p} \sum_{p'\in\mathcal{P}_b} m_{i,b,p',t}}.$$

Note S19. Approach to Calculating Thermal Values

The thermodynamic limit is obtained by calculating the minimum energy required for a chemical process under ideal conditions, thereby revealing the "energy bandwidth" between current practice and the theoretical optimum[27,28]. The framework is applied to systematically evaluate eight lithium-ion battery recycling processes and to quantify their ultimate energy-saving potential, providing an evidence base for decarbonization strategies.

Theoretical minimum energy (TME) is defined as the net reaction enthalpy change (ΔH) required to complete a chemical transformation at a specific process temperature ($T_{process}$). Theoretical Minimum Energy = $\Delta H_{reaction} * T_{process}$. ΔH represents the total energy that the system must absorb or release to break old chemical bonds and form new ones during a reaction, more directly reflecting the energy input required for the process.

Thermodynamic limit builds upon the theoretical minimum energy by further considering the additional heat required to raise all reactants from standard ambient conditions (298.15 K, 1 bar) to the process temperature ($T_{process}$). This heat includes sensible heat ($\Delta Q_{sensible}$) and latent heat (Q_{latent}).

$$Thermodynamic\ limit = \Delta H_{reaction} * T_{process} + \Delta Q_{sensible} + Q_{\text{latent}}$$

Where, sensible heat ($\Delta Q_{sensible}$) is calculated by integrating over all reactants, considering their molar amount (n_i) and temperature-dependent molar heat capacities ($C_{P,i}(T)$)

$$\Delta Q_{sensible} = \sum_i \int_{298.15K}^{T_{process}} n_i * C_{P,i}(T)dT$$

Latent heat (Q_{latent}) accounts for the energy absorbed during phase changes (e.g., melting, vaporization) that may occur as reactants are heated:

$$Q_{\text{latent}} = \sum_i n_i * \Delta H_{phase\ change,j}$$

This "thermodynamic limit" represents the lowest energy consumption level achievable by an idealized, perfectly insulated process, and is a key indicator for measuring the gap between current technology and the ultimate goal permitted by physical laws.

The effective utilization of exothermic heat fundamentally depends on its "thermal quality" (i.e., temperature).

- For Pyrometallurgical Processes (typically > 1000°C): In such processes, like high-temperature smelting furnaces, the system itself is a highly integrated thermal energy unit. Any exothermic heat released by chemical reactions is high-temperature, high-quality thermal energy that can be directly and efficiently used to maintain the thermal balance within the furnace, thereby directly reducing the need for external fuel input. Therefore, this report stipulates: For pyrometallurgical processes, reaction exothermic heat is considered 100% utilizable.
    - Calculation Rule: If the reaction enthalpy change is negative (exothermic), the utilizable heat (Q_{util}) equals the absolute value of the exothermic heat (Q_{util}= $|\Delta H_{reaction}|$). In this case, the theoretical minimum energy is negative or zero, meaning the process is self-sustaining from a chemical reaction perspective. The final thermodynamic limit (practical minimum energy) is then the total heating demand minus this utilizable exothermic heat: Thermodynamic Limit = $\Delta Q_{sensible}$ + $Q_{\text{latent}}) - Q_{util}$. If this result is negative, it indicates that the process, under ideal conditions, even has high-quality waste heat output.
- For Hydrometallurgical Processes (typically < 100°C): Hydrometallurgical processes, such as acid leaching, extraction, and precipitation, generate exothermic heat that is low-temperature, low-quality thermal energy. This heat is usually insufficient to directly drive other unit operations requiring higher temperatures (e.g., solvent evaporation, crystallization mother liquor concentration). To utilize it would require additional technologies like heat pumps, which involve significant capital investment and operating costs. Following a conservative and pragmatic principle, this report stipulates: For hydrometallurgical processes, reaction exothermic heat is considered non-utilizable to offset other energy inputs.
    - Calculation Rule: Even if the reaction enthalpy change is negative, the utilizable heat (Q_{util}) is recorded as zero. A negative reaction enthalpy only indicates that this reaction step dissipates heat to the environment, which needs to be managed (e.g., by cooling water), but it cannot reduce the energy that must be input for other steps

(e.g., heating the leachate). Therefore, its thermodynamic limit calculation formula remains unchanged: Thermodynamic Limit = $\Delta H_{reaction} + \Delta Q_{sensible} + Q_{\mathrm{latent}}$.

Hydrometallurgical process temperatures are uniformly set at 80°C (353.15 K), pyrometallurgical processes at 1500°C (1773.15 K), and pyro-hydrometallurgical combined processes are calculated in segments according to the specific material flows in the LCI inventory.

Note S20. Process classification description

We compiled publicly available, project-level information from approximately 300 licensed recyclers (equipment lists, processed chemistries, rated capacity, geolocation). In parallel, we used the Tianyancha (https://www.tianyancha.com) enterprise registry to classify informal recyclers by firm size (Based on Tianyancha's big data model, combined with corporate operational metrics such as total assets, operating profit, and workforce size, a comprehensive calculation system categorizes enterprises into four size classifications: large, medium, small, and micro). Medium-sized informal firms were mapped to medium-emission processes, while small/micro firms were mapped to high-emission processes.

Building on these data, we constructed province-level process portfolios that reflect the observed distribution of low, medium, and high emission technologies while explicitly regionalizing grid factors. We categorize the sector into eight representative configurations (by process type, feedstock chemistry, and scale/formality):

1. Low-emission Pyro-hydrometallurgy combined (NCM) formal;
2. Low-emission hydrometallurgy (NCM) —formal;
3. Low-emission hydrometallurgy (LFP) —formal;
4. Medium-emission hydrometallurgy (NCM) —medium-sized;
5. Medium-emission pyrometallurgy (LFP) —medium-sized;
6. High-emission hydrometallurgy (NCM) —small-scale;
7. High-emission hydrometallurgy (LFP) —small-scale;
8. High-emission pyrometallurgy (NCM) —small-scale.

Province-level shares of the three emission tiers were derived by combining licensed capacity weights and firm-size distributions, and then used to compute weighted LCIs and environmental impacts for each province.

- Low-emission: Formal enterprises included in the MIIT (2024) White List, meeting ⩾90% lithium and ⩾98% nickel–cobalt–manganese recovery, with stringent wastewater and air-emission controls; typically advanced hydrometallurgy and pyro-hydro hybrid routes. Verified enterprise data included minimum requirements for power battery recyclers: USD 1.43 million registered capital, USD 0.71 million paid-in capital, and ⩾5,000 t yr^{-1} operational capacity[29].

- Medium-emission: Mid-scale firms using semi-industrial hydrometallurgical or pyrometallurgical processes with moderate recovery and partial pollution control.

- High-emission: Small-scale workshops employing rudimentary, unregulated practices (e.g., crude acid leaching or open burning) with low recovery and high emissions.

Province-specific electricity mixes/emission factors are applied to the electricity inputs to obtain province-differentiated impacts.

Supplementary Tables

Table S1. 364 cities information

EN-Province	CN-City	EN-City	City code	City type
Anhui	安庆市	Anqing	340800	Prefecture-level City
Anhui	蚌埠市	Bengbu	340300	Prefecture-level City
Anhui	亳州市	Bozhou	341600	Prefecture-level City
Anhui	池州市	Chizhou	341700	Prefecture-level City
Anhui	滁州市	Chuzhou	341100	Prefecture-level City
Anhui	阜阳市	Fuyang	341200	Prefecture-level City
Anhui	合肥市	Hefei	340100	Prefecture-level City
Anhui	淮北市	Huaibei	340600	Prefecture-level City
Anhui	淮南市	Huainan	340400	Prefecture-level City

Anhui	黄山市	Huangshan	341000	Prefecture-level City
Anhui	六安市	Lu'an	341500	Prefecture - level city
Anhui	马鞍山市	Ma'anshan	340500	Prefecture - level city
Anhui	宿州市	Suzhou	341300	Prefecture - level city
Anhui	铜陵市	Tongling	340700	Prefecture - level city
Anhui	芜湖市	Wuhu	340200	Prefecture - level city
Anhui	宣城市	Xuancheng	341800	Prefecture - level city
Beijing	北京市	Beijing	110000	Municipality directly under the Central Government
Fujian	福州市	Fuzhou	350100	Prefecture-level City
Fujian	龙岩市	Longyan	350800	Prefecture - level city
Fujian	南平市	Nanping	350700	Prefecture - level city
Fujian	宁德市	Ningde	350900	Prefecture - level city

Fujian	莆田市	Putian	350300	Prefecture - level city
Fujian	泉州市	Quanzhou	350500	Prefecture - level city
Fujian	三明市	Sanming	350400	Prefecture - level city
Fujian	厦门市	Xiamen	350200	Prefecture - level city
Fujian	漳州市	Zhangzhou	350600	Prefecture - level city
Gansu	白银市	Baiyin	620400	Prefecture-level City
Gansu	定西市	Dingxi	621100	Prefecture-level City
Gansu	甘南藏族自治州	Gannan Tibetan Autonomous Prefecture	623000	Autonomous Prefecture
Gansu	嘉峪关市	Jiayuguan	620200	Prefecture-level City
Gansu	金昌市	Jinchang	620300	Prefecture-level City
Gansu	酒泉市	Jiuquan	620900	Prefecture - level city

Gansu	兰州市	Lanzhou	620100	Prefecture - level city
Gansu	临夏回族自治州	Linxia Hui Autonomous Prefecture	622900	Autonomous prefecture
Gansu	陇南市	Longnan	621200	Prefecture - level city
Gansu	平凉市	Pingliang	620800	Prefecture - level city
Gansu	庆阳市	Qingyang	621000	Prefecture - level city
Gansu	天水市	Tianshui	620500	Prefecture - level city
Gansu	武威市	Wuwei	620600	Prefecture - level city
Gansu	张掖市	Zhangye	620700	Prefecture - level city
Guangdong	潮州市	Chaozhou	445100	Prefecture-level City
Guangdong	东莞市	Dongguan	441900	Prefecture-level City
Guangdong	佛山市	Foshan	440600	Prefecture-level City

Guangdong	广州市	Guangzhou	440100	Prefecture-level City
Guangdong	河源市	Heyuan	441600	Prefecture-level City
Guangdong	惠州市	Huizhou	441300	Prefecture-level City
Guangdong	江门市	Jiangmen	440700	Prefecture-level City
Guangdong	揭阳市	Jieyang	445200	Prefecture-level City
Guangdong	茂名市	Maoming	440900	Prefecture - level city
Guangdong	梅州市	Meizhou	441400	Prefecture - level city
Guangdong	清远市	Qingyuan	441800	Prefecture - level city
Guangdong	汕头市	Shantou	440500	Prefecture - level city
Guangdong	汕尾市	Shanwei	441500	Prefecture - level city
Guangdong	韶关市	Shaoguan	440200	Prefecture - level city
Guangdong	深圳市	Shenzhen	440300	Prefecture - level city

Guangdong	阳江市	Yangjiang	441700	Prefecture - level city
Guangdong	云浮市	Yunfu	445300	Prefecture - level city
Guangdong	湛江市	Zhanjiang	440800	Prefecture - level city
Guangdong	肇庆市	Zhaoqing	441200	Prefecture - level city
Guangdong	中山市	Zhongshan	442000	Prefecture - level city
Guangdong	珠海市	Zhuhai	440400	Prefecture - level city
Guangxi	百色市	Baise	451000	Prefecture-level City
Guangxi	北海市	Beihai	450500	Prefecture-level City
Guangxi	崇左市	Chongzuo	451400	Prefecture-level City
Guangxi	防城港市	Fangchenggang	450600	Prefecture-level City
Guangxi	贵港市	Guigang	450800	Prefecture-level City
Guangxi	桂林市	Guilin	450300	Prefecture-level City

Guangxi	河池市	Hechi	451200	Prefecture-level City
Guangxi	贺州市	Hezhou	451100	Prefecture-level City
Guangxi	来宾市	Laibin	451300	Prefecture - level city
Guangxi	柳州市	Liuzhou	450200	Prefecture - level city
Guangxi	南宁市	Nanning	450100	Prefecture - level city
Guangxi	钦州市	Qinzhou	450700	Prefecture - level city
Guangxi	梧州市	Wuzhou	450400	Prefecture - level city
Guangxi	玉林市	Yulin	450900	Prefecture - level city
Guizhou	安顺市	Anshun	520400	Prefecture-level City
Guizhou	毕节市	Bijie	520500	Prefecture-level City
Guizhou	贵阳市	Guiyang	520100	Prefecture-level City
Guizhou	六盘水市	Liupanshui	520200	Prefecture - level city

Guizhou	黔东南苗族侗族自治州	Qiandongnan Miao and Dong Autonomous Prefecture	522600	Autonomous prefecture
Guizhou	黔南布依族苗族自治州	Qiannan Buyi and Miao Autonomous Prefecture	522700	Autonomous prefecture
Guizhou	黔西南布依族苗族自治州	Qianxinan Buyi and Miao Autonomous Prefecture	522300	Autonomous prefecture
Guizhou	铜仁市	Tongren	520600	Prefecture - level city
Guizhou	遵义市	Zunyi	520300	Prefecture - level city
Hainan	白沙黎族自治县	Baisha Li Autonomous County	469025	County directly under the jurisdiction of the province
Hainan	保亭黎族苗族自治县	Baoting Li and Miao Autonomous County	469029	County directly under the jurisdiction of the province

Hainan	昌江黎族自治县	Changjiang Li Autonomous County	469026	County directly under the jurisdiction of the province
Hainan	澄迈县	Chengmai County	469023	County directly under the jurisdiction of the province
Hainan	儋州市	Danzhou	460400	Prefecture-level City
Hainan	定安县	Ding'an County	469021	County directly under the jurisdiction of the province
Hainan	东方市	Dongfang	469007	County directly under the jurisdiction of the province
Hainan	海口市	Haikou	460100	Prefecture-level City
Hainan	乐东黎族自治县	Ledong Li Autonomous County	469027	County directly under provincial jurisdiction
Hainan	临高县	Lingao County	469024	County directly under provincial jurisdiction
Hainan	陵水黎族自治县	Lingshui Li Autonomous County	469028	County directly under provincial jurisdiction
Hainan	琼海市	Qionghai	469002	County directly under provincial jurisdiction

Hainan	琼中黎族苗族自治县	Qiongzhong Li and Miao Autonomous County	469030	County directly under provincial jurisdiction
Hainan	三沙市	Sansha	460300	Prefecture - level city
Hainan	三亚市	Sanya	460200	Prefecture - level city
Hainan	屯昌县	Tunchang County	469022	County directly under provincial jurisdiction
Hainan	万宁市	Wanning	469006	County directly under provincial jurisdiction
Hainan	文昌市	Wenchang	469005	County directly under provincial jurisdiction
Hainan	五指山市	Wuzhishan	469001	County directly under provincial jurisdiction
Hebei	保定市	Baoding	130600	Prefecture-level City
Hebei	沧州市	Cangzhou	130900	Prefecture-level City
Hebei	承德市	Chengde	130800	Prefecture-level City
Hebei	邯郸市	Handan	130400	Prefecture-level City

Hebei	衡水市	Hengshui	131100	Prefecture-level City
Hebei	廊坊市	Langfang	131000	Prefecture - level city
Hebei	秦皇岛市	Qinhuangdao	130300	Prefecture - level city
Hebei	石家庄市	Shijiazhuang	130100	Prefecture - level city
Hebei	唐山市	Tangshan	130200	Prefecture - level city
Hebei	邢台市	Xingtai	130500	Prefecture - level city
Hebei	张家口市	Zhangjiakou	130700	Prefecture - level city
Henan	安阳市	Anyang	410500	Prefecture-level City
Henan	鹤壁市	Hebi	410600	Prefecture-level City
Henan	济源市	Jiyuan	419001	County directly under the jurisdiction of the province
Henan	焦作市	Jiaozuo	410800	Prefecture-level City
Henan	开封市	Kaifeng	410200	Prefecture - level city

Henan	洛阳市	Luoyang	410300	Prefecture - level city
Henan	漯河市	Luohe	411100	Prefecture - level city
Henan	南阳市	Nanyang	411300	Prefecture - level city
Henan	平顶山市	Pingdingshan	410400	Prefecture - level city
Henan	濮阳市	Puyang	410900	Prefecture - level city
Henan	三门峡市	Sanmenxia	411200	Prefecture - level city
Henan	商丘市	Shangqiu	411400	Prefecture - level city
Henan	新乡市	Xinxiang	410700	Prefecture - level city
Henan	信阳市	Xinyang	411500	Prefecture - level city
Henan	许昌市	Xuchang	411000	Prefecture - level city
Henan	郑州市	Zhengzhou	410100	Prefecture - level city
Henan	周口市	Zhoukou	411600	Prefecture - level city

Henan	驻马店市	Zhumadian	411700	Prefecture - level city
Heilongjiang	大庆市	Daqing	230600	Prefecture-level City
Heilongjiang	大兴安岭地区	Daxing'anling Prefecture	232700	Prefecture
Heilongjiang	哈尔滨市	Harbin	230100	Prefecture-level City
Heilongjiang	鹤岗市	Hegang	230400	Prefecture-level City
Heilongjiang	黑河市	Heihe	231100	Prefecture-level City
Heilongjiang	鸡西市	Jixi	230300	Prefecture-level City
Heilongjiang	佳木斯市	Jiamusi	230800	Prefecture-level City
Heilongjiang	牡丹江市	Mudanjiang	231000	Prefecture - level city
Heilongjiang	七台河市	Qitaihe	230900	Prefecture - level city
Heilongjiang	齐齐哈尔市	Qiqihar	230200	Prefecture - level city

Heilongjiang	双鸭山市	Shuangyashan	230500	Prefecture - level city
Heilongjiang	绥化市	Suihua	231200	Prefecture - level city
Heilongjiang	伊春市	Yichun	230700	Prefecture - level city
Hubei	鄂州市	Ezhou	420700	Prefecture-level City
Hubei	恩施土家族苗族自治州	Enshi Tujia and Miao Autonomous Prefecture	422800	Autonomous Prefecture
Hubei	黄冈市	Huanggang	421100	Prefecture-level City
Hubei	黄石市	Huangshi	420200	Prefecture-level City
Hubei	荆门市	Jingmen	420800	Prefecture-level City
Hubei	荆州市	Jingzhou	421000	Prefecture-level City
Hubei	潜江市	Qianjiang	429005	County directly under provincial jurisdiction
Hubei	神农架林区	Shennongjia Forestry District	429021	County directly under provincial jurisdiction

Hubei	十堰市	Shiyan	420300	Prefecture - level city
Hubei	随州市	Suizhou	421300	Prefecture - level city
Hubei	天门市	Tianmen	429006	County directly under provincial jurisdiction
Hubei	武汉市	Wuhan	420100	Prefecture - level city
Hubei	仙桃市	Xiantao	429004	County directly under provincial jurisdiction
Hubei	咸宁市	Xianning	421200	Prefecture - level city
Hubei	襄阳市	Xiangyang	420600	Prefecture - level city
Hubei	孝感市	Xiaogan	420900	Prefecture - level city
Hubei	宜昌市	Yichang	420500	Prefecture - level city
Hunan	常德市	Changde	430700	Prefecture-level City
Hunan	郴州市	Chenzhou	431000	Prefecture-level City
Hunan	衡阳市	Hengyang	430400	Prefecture-level City

Hunan	怀化市	Huaihua	431200	Prefecture-level City
Hunan	娄底市	Loudi	431300	Prefecture - level city
Hunan	邵阳市	Shaoyang	430500	Prefecture - level city
Hunan	湘潭市	Xiangtan	430300	Prefecture - level city
Hunan	湘西土家族苗族自治州	Xiangxi Tujia and Miao Autonomous Prefecture	433100	Autonomous prefecture
Hunan	益阳市	Yiyang	430900	Prefecture - level city
Hunan	永州市	Yongzhou	431100	Prefecture - level city
Hunan	岳阳市	Yueyang	430600	Prefecture - level city
Hunan	张家界市	Zhangjiajie	430800	Prefecture - level city
Hunan	长沙市	Changsha	430100	Prefecture - level city
Hunan	株洲市	Zhuzhou	430200	Prefecture - level city

Jilin	白城市	Baicheng	220800	Prefecture-level City
Jilin	白山市	Baishan	220600	Prefecture-level City
Jilin	吉林市	Jilin	220200	Prefecture-level City
Jilin	辽源市	Liaoyuan	220400	Prefecture - level city
Jilin	四平市	Siping	220300	Prefecture - level city
Jilin	松原市	Songyuan	220700	Prefecture - level city
Jilin	通化市	Tonghua	220500	Prefecture - level city
Jilin	延边朝鲜族自治州	Yanbian Korean Autonomous Prefecture	222400	Autonomous prefecture
Jilin	长春市	Changchun	220100	Prefecture - level city
Jiangsu	常州市	Changzhou	320400	Prefecture-level City
Jiangsu	淮安市	Huai'an	320800	Prefecture-level City

Jiangsu	连云港市	Lianyungang	320700	Prefecture - level city
Jiangsu	南京市	Nanjing	320100	Prefecture - level city
Jiangsu	南通市	Nantong	320600	Prefecture - level city
Jiangsu	苏州市	Suzhou	320500	Prefecture - level city
Jiangsu	宿迁市	Suqian	321300	Prefecture - level city
Jiangsu	泰州市	Taizhou	321200	Prefecture - level city
Jiangsu	无锡市	Wuxi	320200	Prefecture - level city
Jiangsu	徐州市	Xuzhou	320300	Prefecture - level city
Jiangsu	盐城市	Yancheng	320900	Prefecture - level city
Jiangsu	扬州市	Yangzhou	321000	Prefecture - level city
Jiangsu	镇江市	Zhenjiang	321100	Prefecture - level city
Jiangxi	抚州市	Fuzhou	361000	Prefecture-level City

Jiangxi	赣州市	Ganzhou	360700	Prefecture-level City
Jiangxi	吉安市	Ji'an	360800	Prefecture-level City
Jiangxi	景德镇市	Jingdezhen	360200	Prefecture-level City
Jiangxi	九江市	Jiujiang	360400	Prefecture-level City
Jiangxi	南昌市	Nanchang	360100	Prefecture - level city
Jiangxi	萍乡市	Pingxiang	360300	Prefecture - level city
Jiangxi	上饶市	Shangrao	361100	Prefecture - level city
Jiangxi	新余市	Xinyu	360500	Prefecture - level city
Jiangxi	宜春市	Yichun	360900	Prefecture - level city
Jiangxi	鹰潭市	Yingtan	360600	Prefecture - level city
Liaoning	鞍山市	Anshan	210300	Prefecture-level City
Liaoning	本溪市	Benxi	210500	Prefecture-level City

Liaoning	朝阳市	Chaoyang	211300	Prefecture-level City
Liaoning	大连市	Dalian	210200	Prefecture-level City
Liaoning	丹东市	Dandong	210600	Prefecture-level City
Liaoning	抚顺市	Fushun	210400	Prefecture-level City
Liaoning	阜新市	Fuxin	210900	Prefecture-level City
Liaoning	葫芦岛市	Huludao	211400	Prefecture-level City
Liaoning	锦州市	Jinzhou	210700	Prefecture-level City
Liaoning	辽阳市	Liaoyang	211000	Prefecture - level city
Liaoning	盘锦市	Panjin	211100	Prefecture - level city
Liaoning	沈阳市	Shenyang	210100	Prefecture - level city
Liaoning	铁岭市	Tieling	211200	Prefecture - level city
Liaoning	营口市	Yingkou	210800	Prefecture - level city

Inner Mongolia	阿拉善盟	Alxa League	152900	League
Inner Mongolia	巴彦淖尔市	Bayannur	150800	Prefecture-level City
Inner Mongolia	包头市	Baotou	150200	Prefecture-level City
Inner Mongolia	赤峰市	Chifeng	150400	Prefecture-level City
Inner Mongolia	鄂尔多斯市	Ordos	150600	Prefecture-level City
Inner Mongolia	呼和浩特市	Hohhot	150100	Prefecture-level City
Inner Mongolia	呼伦贝尔市	Hulunbuir	150700	Prefecture-level City
Inner Mongolia	通辽市	Tongliao	150500	Prefecture - level city
Inner Mongolia	乌海市	Wuhai	150300	Prefecture - level city
Inner Mongolia	乌兰察布市	Ulanqab	150900	Prefecture - level city
Inner Mongolia	锡林郭勒盟	Xilingol League	152500	League
Inner Mongolia	兴安盟	Xing'an League	152200	League

Ningxia Hui	固原市	Guyuan	640400	Prefecture-level City
Ningxia Hui	石嘴山市	Shizuishan	640200	Prefecture - level city
Ningxia Hui	吴忠市	Wuzhong	640300	Prefecture - level city
Ningxia Hui	银川市	Yinchuan	640100	Prefecture - level city
Ningxia Hui	中卫市	Zhongwei	640500	Prefecture - level city
Qinghai	果洛藏族自治州	Golog Tibetan Autonomous Prefecture	632600	Autonomous Prefecture
Qinghai	海北藏族自治州	Haibei Tibetan Autonomous Prefecture	632200	Autonomous Prefecture
Qinghai	海东市	Haidong	630200	Prefecture-level City
Qinghai	海南藏族自治州	Hainan Tibetan Autonomous Prefecture	632500	Autonomous Prefecture

Qinghai	海西蒙古族藏族自治州	Haixi Mongolian and Tibetan Autonomous Prefecture	632800	Autonomous Prefecture
Qinghai	黄南藏族自治州	Huangnan Tibetan Autonomous Prefecture	632300	Autonomous Prefecture
Qinghai	西宁市	Xining	630100	Prefecture - level city
Qinghai	玉树藏族自治州	Yushu Tibetan Autonomous Prefecture	632700	Autonomous prefecture
Shandong	滨州市	Binzhou	371600	Prefecture-level City
Shandong	德州市	Dezhou	371400	Prefecture-level City
Shandong	东营市	Dongying	370500	Prefecture-level City
Shandong	菏泽市	Heze	371700	Prefecture-level City
Shandong	济南市	Jinan	370100	Prefecture-level City
Shandong	济宁市	Jining	370800	Prefecture-level City

Shandong	聊城市	Liaocheng	371500	Prefecture - level city
Shandong	临沂市	Linyi	371300	Prefecture - level city
Shandong	青岛市	Qingdao	370200	Prefecture - level city
Shandong	日照市	Rizhao	371100	Prefecture - level city
Shandong	泰安市	Tai'an	370900	Prefecture - level city
Shandong	威海市	Weihai	371000	Prefecture - level city
Shandong	潍坊市	Weifang	370700	Prefecture - level city
Shandong	烟台市	Yantai	370600	Prefecture - level city
Shandong	枣庄市	Zaozhuang	370400	Prefecture - level city
Shandong	淄博市	Zibo	370300	Prefecture - level city
Shanxi	大同市	Datong	140200	Prefecture-level City
Shanxi	晋城市	Jincheng	140500	Prefecture-level City

Shanxi	晋中市	Jinzhong	140700	Prefecture-level City
Shanxi	临汾市	Linfen	141000	Prefecture - level city
Shanxi	吕梁市	Lvliang	141100	Prefecture - level city
Shanxi	朔州市	Shuozhou	140600	Prefecture - level city
Shanxi	太原市	Taiyuan	140100	Prefecture - level city
Shanxi	忻州市	Xinzhou	140900	Prefecture - level city
Shanxi	阳泉市	Yangquan	140300	Prefecture - level city
Shanxi	运城市	Yuncheng	140800	Prefecture - level city
Shanxi	长治市	Changzhi	140400	Prefecture - level city
Shaanxi	安康市	Ankang	610900	Prefecture-level City
Shaanxi	宝鸡市	Baoji	610300	Prefecture-level City
Shaanxi	汉中市	Hanzhong	610700	Prefecture-level City

Shaanxi	商洛市	Shangluo	611000	Prefecture - level city
Shaanxi	铜川市	Tongchuan	610200	Prefecture - level city
Shaanxi	渭南市	Weinan	610500	Prefecture - level city
Shaanxi	西安市	Xi'an	610100	Prefecture - level city
Shaanxi	咸阳市	Xianyang	610400	Prefecture - level city
Shaanxi	延安市	Yan'an	610600	Prefecture - level city
Shaanxi	榆林市	Yulin	610800	Prefecture - level city
Shanghai	上海市	Shanghai	310000	Municipality directly under the Central Government
Sichuan	阿坝藏族羌族自治州	Aba Tibetan and Qiang Autonomous Prefecture	513200	utonomous Prefecture
Sichuan	巴中市	Bazhong	511900	Prefecture-level City
Sichuan	成都市	Chengdu	510100	Prefecture-level City

Sichuan	达州市	Dazhou	511700	Prefecture-level City
Sichuan	德阳市	Deyang	510600	Prefecture-level City
Sichuan	甘孜藏族自治州	Garze Tibetan Autonomous Prefecture	513300	Autonomous Prefecture
Sichuan	广安市	Guang'an	511600	Prefecture-level City
Sichuan	广元市	Guangyuan	510800	Prefecture-level City
Sichuan	乐山市	Leshan	511100	Prefecture - level city
Sichuan	凉山彝族自治州	Liangshan Yi Autonomous Prefecture	513400	Autonomous prefecture
Sichuan	泸州市	Luzhou	510500	Prefecture - level city
Sichuan	眉山市	Meishan	511400	Prefecture - level city
Sichuan	绵阳市	Mianyang	510700	Prefecture - level city
Sichuan	南充市	Nanchong	511300	Prefecture - level city

Sichuan	内江市	Neijiang	511000	Prefecture - level city
Sichuan	攀枝花市	Panzhihua	510400	Prefecture - level city
Sichuan	遂宁市	Suining	510900	Prefecture - level city
Sichuan	雅安市	Yaan	511800	Prefecture - level city
Sichuan	宜宾市	Yibin	511500	Prefecture - level city
Sichuan	资阳市	Ziyang	512000	Prefecture - level city
Sichuan	自贡市	Zigong	510300	Prefecture - level city
Tianjin	天津市	Tianjin	120000	Municipality directly under the Central Government
Tibet	阿里地区	Ngari Prefecture	542500	Prefecture
Tibet	昌都市	Changdu	540300	Prefecture-level City
Tibet	拉萨市	Lhasa	540100	Prefecture - level city
Tibet	林芝市	Nyingchi	540400	Prefecture - level city

Tibet	那曲市	Nagqu	540600	Prefecture - level city
Tibet	日喀则市	Shigatse	540200	Prefecture - level city
Tibet	山南市	Shannan	540500	Prefecture - level city
Xinjiang	阿克苏地区	Aksu Prefecture	652900	Prefecture
Xinjiang	阿拉尔市	Aral	659002	County directly under the jurisdiction of the province
Xinjiang	阿勒泰地区	Altay Prefecture	654300	Prefecture
Xinjiang	巴音郭楞蒙古自治州	Bayingolin Mongolian Autonomous Prefecture	652800	Autonomous Prefecture
Xinjiang	北屯市	Beitun	659005	County directly under the jurisdiction of the province
Xinjiang	博尔塔拉蒙古自治州	Bortala Mongolian Autonomous Prefecture	652700	Autonomous Prefecture
Xinjiang	昌吉回族自治州	Changji Hui Autonomous Prefecture	652300	Autonomous Prefecture

Xinjiang	哈密市	Hami	650500	Prefecture-level City
Xinjiang	和田地区	Hotan Prefecture	653200	Prefecture
Xinjiang	喀什地区	Kashgar Prefecture	653100	Prefecture
Xinjiang	克拉玛依市	Karamay	650200	Prefecture - level city
Xinjiang	克孜勒苏柯尔克孜自治州	Kizilsu Kirgiz Autonomous Prefecture	653000	Autonomous prefecture
Xinjiang	石河子市	Shihezi	659001	County directly under provincial jurisdiction
Xinjiang	双河市	Shuanghe	659007	County directly under provincial jurisdiction
Xinjiang	塔城地区	Tacheng Prefecture	654200	Prefecture
Xinjiang	铁门关市	Tiemenguan	659006	County directly under provincial jurisdiction
Xinjiang	图木舒克市	Tumushuke	659003	County directly under provincial jurisdiction
Xinjiang	吐鲁番市	Turpan	650400	Prefecture - level city

Xinjiang	乌鲁木齐市	Urumqi	650100	Prefecture - level city
Xinjiang	五家渠市	Wujiaqu	659004	County directly under provincial jurisdiction
Xinjiang	伊犁哈萨克自治州	Yili Kazakh Autonomous Prefecture	654000	Autonomous prefecture
Yunnan	保山市	Baoshan	530500	Prefecture-level City
Yunnan	楚雄彝族自治州	Chuxiong Yi Autonomous Prefecture	532300	Autonomous Prefecture
Yunnan	大理白族自治州	Dali Bai Autonomous Prefecture	532900	Autonomous Prefecture
Yunnan	德宏傣族景颇族自治州	Dehong Dai and Jingpo Autonomous Prefecture	533100	Autonomous Prefecture
Yunnan	迪庆藏族自治州	Diqing Tibetan Autonomous Prefecture	533400	Autonomous Prefecture

Yunnan	红河哈尼族彝族自治州	Honghe Hani and Yi Autonomous Prefecture	532500	Autonomous Prefecture
Yunnan	昆明市	Kunming	530100	Prefecture - level city
Yunnan	丽江市	Lijiang	530700	Prefecture - level city
Yunnan	临沧市	Lincang	530900	Prefecture - level city
Yunnan	怒江傈僳族自治州	Nujiang Lisu Autonomous Prefecture	533300	Prefecture - level city
Yunnan	普洱市	Pu'er	530800	Prefecture - level city
Yunnan	曲靖市	Qujing	530300	Prefecture - level city
Yunnan	文山壮族苗族自治州	Wenshan Zhuang and Miao Autonomous Prefecture	532600	Autonomous prefecture
Yunnan	西双版纳傣族自治州	Xishuangbanna Dai Autonomous Prefecture	532800	Autonomous prefecture

Yunnan	玉溪市	Yuxi	530400	Prefecture - level city
Yunnan	昭通市	Zhaotong	530600	Prefecture - level city
Zhejiang	杭州市	Hangzhou	330100	Prefecture-level City
Zhejiang	湖州市	Huzhou	330500	Prefecture-level City
Zhejiang	嘉兴市	Jiaxing	330400	Prefecture-level City
Zhejiang	金华市	Jinhua	330700	Prefecture-level City
Zhejiang	丽水市	Lishui	331100	Prefecture - level city
Zhejiang	宁波市	Ningbo	330200	Prefecture - level city
Zhejiang	衢州市	Quzhou	330800	Prefecture - level city
Zhejiang	绍兴市	Shaoxing	330600	Prefecture - level city
Zhejiang	台州市	Taizhou	331000	Prefecture - level city
Zhejiang	温州市	Wenzhou	330300	Prefecture - level city

Zhejiang	舟山市	Zhoushan	330900	Prefecture - level city
Chongqing	重庆市	Chongqing	500000	Municipality directly under the Central Government

Table S2. GDP value of cities in Chinese mainland in 2024

No.	City	Province	GDP (RMB billion)	No.	City	Province	GDP (RMB billion)
1	Shanghai	Shanghai	5392.67	51	Zhangzhou City	Fujian	606.37
2	Beijing	Beijing	4984.31	52	Harbin City	Heilongjiang	601.63
3	Shenzhen	Guangdong	3680.19	53	Nanning City	Guangxi	599.54
4	Chongqing	Chongqing	3219.32	54	Jining City	Shandong	586.75
5	Guangzhou	Guangdong	3103.25	55	Luoyang City	Henan	581.86
6	Suzhou (Jiangsu)	Jiangsu	2672.7	56	Guiyang City	Guizhou	577.74
7	Chengdu	Sichuan	2351.13	57	Zhenjiang City	Jiangsu	554
8	Hangzhou	Zhejiang	2186.03	58	Taiyuan City	Shanxi	541.89
9	Wuhan	Hubei	2110.62	59	Huai'an City	Jiangsu	541.3

10	Nanjing	Jiangsu	1850.08	60	Yueyang City	Hunan	512.77
11	Ningbo	Zhejiang	1814.77	61	Wuhu City	Anhui	512.05
12	Tianjin	Tianjin	1802.43	62	Zunyi City	Guizhou	502.72
13	Qingdao	Shandong	1671.95	63	Ganzhou City	Jiangxi	494.05
14	Wuxi	Jiangsu	1626.33	64	Zibo City	Shandong	488.41
15	Changsha	Hunan	1526.88	65	Nanyang City	Henan	487.91
16	Zhengzhou	Henan	1453.21	66	Heze City	Shandong	480.26
17	Fuzhou (Fujian)	Fujian	1423.68	67	Suqian City	Jiangsu	480.19
18	Jinan	Shandong	1352.76	68	Baoding City	Hebei	477.33
19	Hefei	Anhui	1350.77	69	Cangzhou City	Hebei	472.28
20	Foshan	Guangdong	1336.19	70	Handan City	Hebei	470.43
21	Xi'an	Shaanxi	1331.78	71	Lianyungang City	Jiangsu	466.31
22	Quanzhou	Fujian	1309.49	72	Baotou City	Inner Mongolia	457.51
23	Nantong	Jiangsu	1242.19	73	Changde City	Hunan	453.27
24	Dongguan	Guangdong	1228.22	74	Urumqi City	Xinjiang	450.22

25	Changzhou	Jiangsu	1081.36	75	Hengyang City	Hunan	449.17
26	Yantai	Shandong	1078.28	76	Zhuhai City	Guangdong	447.91
27	Tangshan	Hebei	1000.39	77	Mianyang City	Sichuan	434.4
28	Wenzhou	Zhejiang	971.89	78	Dongying City	Shandong	430.77
29	Xuzhou	Jiangsu	953.71	79	Huzhou City	Zhejiang	421.34
30	Dalian	Liaoning	951.69	80	Jiangmen City	Guangdong	421.02
31	Shenyang	Liaoning	902.71	81	Zhongshan City	Guangdong	414.32
32	Xiamen	Fujian	858.9	82	Hohhot City	Inner Mongolia	410.71
33	Shaoxing	Zhejiang	836.86	83	Maoming City	Guangdong	407.2
34	Kunming	Yunnan	827.52	84	Dezhou City	Shandong	404.77
35	Shijiazhuang	Hebei	820.34	85	Chuzhou City	Anhui	403.44
36	Weifang	Shandong	820.32	86	Jiujiang City	Jiangxi	402.18
37	Yangzhou	Jiangsu	780.96	87	Yibin City	Sichuan	400.58
38	Nanchang	Jiangxi	780.04	88	Langfang City	Hebei	390.46
39	Yancheng	Jiangsu	777.92	89	Zhuzhou City	Hunan	390.24

40	Changchun	Jilin	763.22	90	Ningde City	Fujian	390.2
41	Jiaxing	Zhejiang	756.95	91	Zhanjiang City	Guangdong	383.99
42	Yulin （Shaanxi）	Shaanxi	754.87	92	Lanzhou City	Gansu	374.23
43	Taizhou (Jiangsu)	Jiangsu	702.1	93	Weihai City	Shandong	372.86
44	Jinhua	Zhejiang	692.55	94	Shangrao City	Jiangxi	372.09
45	Taizhou	Zhejiang	665.64	95	Yichun City (Jiangxi)	Jiangxi	371.11
46	Linyi	Shandong	655.58	96	Qujing City	Yunnan	367.72
47	Ordos	Inner Mongolia	636.3	97	Zhoukou City	Henan	363.56
48	Yichang	Hubei	619.11	98	Tai'an City	Shandong	362.21
49	Huizhou	Guangdong	613.64	99	Fuyang City	Anhui	360.98
50	Xiangyang City	Hubei	610.24	100	Xinxiang City	Henan	356.97

Table S3. Urban agglomeration

City	Province	Urban agglomeration	City	Province	Urban agglomeration
Zhanjiang City	Guangdong	Beibu Gulf	Fuzhou City (Fujian Province)	Fujian	Coastal Area of Guangdong, Fujian and Zhejiang
Maoming City	Guangdong	Beibu Gulf	Xiamen City	Fujian	Coastal Area of Guangdong, Fujian and Zhejiang
Yangjiang City	Guangdong	Beibu Gulf	Putian City	Fujian	Coastal Area of Guangdong, Fujian and Zhejiang
Nanning City	Guangxi	Beibu Gulf	Quanzhou City	Fujian	Coastal Area of Guangdong, Fujian and Zhejiang
Beihai City	Guangxi	Beibu Gulf	Zhangzhou City	Fujian	Coastal Area of Guangdong, Fujian and Zhejiang
Fangchenggang City	Guangxi	Beibu Gulf	Sanming City	Fujian	Coastal Area of Guangdong, Fujian and Zhejiang
Qinzhou City	Guangxi	Beibu Gulf	Nanping City	Fujian	Coastal Area of Guangdong, Fujian and Zhejiang
Yulin City	Guangxi	Beibu Gulf	Longyan City	Fujian	Coastal Area of Guangdong, Fujian and Zhejiang

Chongzuo City	Guangxi	Beibu Gulf	Wenzhou City	Zhejiang	Coastal Area of Guangdong, Fujian and Zhejiang
Haikou City	Hainan	Beibu Gulf	Lishui City	Zhejiang	Coastal Area of Guangdong, Fujian and Zhejiang
Danzhou City	Hainan	Beibu Gulf	Quzhou City	Zhejiang	Coastal Area of Guangdong, Fujian and Zhejiang
Dongfang City	Hainan	Beibu Gulf	Shangrao City	Jiangxi	Coastal Area of Guangdong, Fujian and Zhejiang
Chengmai County	Hainan	Beibu Gulf	Yingtan City	Jiangxi	Coastal Area of Guangdong, Fujian and Zhejiang
Lingao County	Hainan	Beibu Gulf	Fuzhou City	Jiangxi	Coastal Area of Guangdong, Fujian and Zhejiang
Changjiang Li Autonomous County	Hainan	Beibu Gulf	Ganzhou City	Jiangxi	Coastal Area of Guangdong, Fujian and Zhejiang
Chongqing City	Chongqing	Chengdu - Chongqing Region	Meizhou City	Guangdong	Coastal Area of Guangdong, Fujian and Zhejiang
Chengdu City	Sichuan	Chengdu - Chongqing Region	Ningde City	Fujian	Coastal Area of Guangdong, Fujian and Zhejiang

Deyang City	Sichuan	Chengdu - Chongqing Region	Shantou City	Guangdong	Coastal Area of Guangdong, Fujian and Zhejiang
Mianyang City	Sichuan	Chengdu - Chongqing Region	Chaozhou City	Guangdong	Coastal Area of Guangdong, Fujian and Zhejiang
Guangyuan City	Sichuan	Chengdu - Chongqing Region	Jieyang City	Guangdong	Coastal Area of Guangdong, Fujian and Zhejiang
Suining City	Sichuan	Chengdu - Chongqing Region	Nanchang City	Jiangxi	Middle Reaches of the Yangtze River
Neijiang City	Sichuan	Chengdu - Chongqing Region	Pingxiang City	Jiangxi	Middle Reaches of the Yangtze River
Leshan City	Sichuan	Chengdu - Chongqing Region	Jiujiang City	Jiangxi	Middle Reaches of the Yangtze River
Nanchong City	Sichuan	Chengdu - Chongqing Region	Xinyu City	Jiangxi	Middle Reaches of the Yangtze River
Meishan City	Sichuan	Chengdu - Chongqing Region	Yingtan City	Jiangxi	Middle Reaches of the Yangtze River
Yibin City	Sichuan	Chengdu - Chongqing Region	Jingdezhen City	Jiangxi	Middle Reaches of the Yangtze River
Guang'an City	Sichuan	Chengdu - Chongqing	Ji'an City	Jiangxi	Middle Reaches of the Yangtze River

		Region			
Dazhou City	Sichuan	Chengdu - Chongqing Region	Yichun City	Jiangxi	Middle Reaches of the Yangtze River
Ya'an City	Sichuan	Chengdu - Chongqing Region	Fuzhou City (Jiangxi Province)	Jiangxi	Middle Reaches of the Yangtze River
Bazhong City	Sichuan	Chengdu - Chongqing Region	Wuhan City	Hubei	Middle Reaches of the Yangtze River
Ziyang City	Sichuan	Chengdu - Chongqing Region	Huangshi City	Hubei	Middle Reaches of the Yangtze River
Kunming City	Yunnan	Central Yunnan	Yichang City	Hubei	Middle Reaches of the Yangtze River
Qujing City	Yunnan	Central Yunnan	Xiangyang City	Hubei	Middle Reaches of the Yangtze River
Yuxi City	Yunnan	Central Yunnan	Ezhou City	Hubei	Middle Reaches of the Yangtze River
Yuncheng City	Shanxi	Guanzhong Plain	Jingmen City	Hubei	Middle Reaches of the Yangtze River
Linfen City	Shanxi	Guanzhong Plain	Xiaogan City	Hubei	Middle Reaches of the Yangtze River
Xi'an City	Shaanxi	Guanzhong Plain	Jingzhou City	Hubei	Middle Reaches of the Yangtze River
Baoji City	Shaanxi	Guanzhong Plain	Huanggang City	Hubei	Middle Reaches of the Yangtze River
Xianyang City	Shaanxi	Guanzhong Plain	Xianning City	Hubei	Middle Reaches of the Yangtze River

Weinan City	Shaanxi	Guanzhong Plain	Suizhou City	Hubei	Middle Reaches of the Yangtze River
Shangluo City	Shaanxi	Guanzhong Plain	Xiantao City	Hubei	Middle Reaches of the Yangtze River
Tianshui City	Gansu	Guanzhong Plain	Qianjiang City	Hubei	Middle Reaches of the Yangtze River
Pingliang City	Gansu	Guanzhong Plain	Tianmen City	Hubei	Middle Reaches of the Yangtze River
Qingyang City	Gansu	Guanzhong Plain	Changsha City	Hunan	Middle Reaches of the Yangtze River
Changchun City	Jilin	Harbin - Changchun Region	Zhuzhou City	Hunan	Middle Reaches of the Yangtze River
Jilin City	Jilin	Harbin - Changchun Region	Xiangtan City	Hunan	Middle Reaches of the Yangtze River
Siping City	Jilin	Harbin - Changchun Region	Hengyang City	Hunan	Middle Reaches of the Yangtze River
Liaoyuan City	Jilin	Harbin - Changchun Region	Shaoyang City	Hunan	Middle Reaches of the Yangtze River
Songyuan City	Jilin	Harbin - Changchun Region	Yueyang City	Hunan	Middle Reaches of the Yangtze River
Yanbian Korean Autonomous Prefecture	Jilin	Harbin - Changchun Region	Changde City	Hunan	Middle Reaches of the Yangtze River

Harbin City	Heilongjiang	Harbin - Changchun Region	Zhangjiajie City	Hunan	Middle Reaches of the Yangtze River
Qiqihaer City	Heilongjiang	Harbin - Changchun Region	Yiyang City	Hunan	Middle Reaches of the Yangtze River
Daqing City	Heilongjiang	Harbin - Changchun Region	Chenzhou City	Hunan	Middle Reaches of the Yangtze River
Mudanjiang City	Heilongjiang	Harbin - Changchun Region	Yongzhou City	Hunan	Middle Reaches of the Yangtze River
Suihua City	Heilongjiang	Harbin - Changchun Region	Huaihua City	Hunan	Middle Reaches of the Yangtze River
Hohhot City	Inner Mongolia	Hohhot - Baotou - Ordos - Yulin Region	Loudi City	Hunan	Middle Reaches of the Yangtze River
Baotou City	Inner Mongolia	Hohhot - Baotou - Ordos - Yulin Region	Xiangxi Tujia and Miao Autonomous Prefecture	Hunan	Middle Reaches of the Yangtze River
Ordos City	Inner Mongolia	Hohhot - Baotou - Ordos - Yulin Region	Shanghai City	Shanghai	Yangtze River Delta Region
Yulin City	Shaanxi	Hohhot - Baotou - Ordos - Yulin Region	Nanjing City	Jiangsu	Yangtze River Delta Region

Beijing	Beijing	Beijing - Tianjin - Hebei Region	Wuxi City	Jiangsu	Yangtze River Delta Region
Tianjin City	Tianjin	Beijing - Tianjin - Hebei Region	Changzhou City	Jiangsu	Yangtze River Delta Region
Shijiazhuang City	Hebei	Beijing - Tianjin - Hebei Region	Suzhou City	Jiangsu	Yangtze River Delta Region
Tangshan City	Hebei	Beijing - Tianjin - Hebei Region	Nantong City	Jiangsu	Yangtze River Delta Region
Qinhuangdao City	Hebei	Beijing - Tianjin - Hebei Region	Yancheng City	Jiangsu	Yangtze River Delta Region
Handan City	Hebei	Beijing - Tianjin - Hebei Region	Yangzhou City	Jiangsu	Yangtze River Delta Region
Xingtai City	Hebei	Beijing - Tianjin - Hebei Region	Zhenjiang City	Jiangsu	Yangtze River Delta Region
Baoding City	Hebei	Beijing - Tianjin - Hebei Region	Taizhou City	Jiangsu	Yangtze River Delta Region
Zhangjiakou City	Hebei	Beijing - Tianjin - Hebei Region	Hangzhou City	Zhejiang	Yangtze River Delta Region
Chengde City	Hebei	Beijing - Tianjin - Hebei	Ningbo City	Zhejiang	Yangtze River Delta Region

		Region			
Cangzhou City	Hebei	Beijing - Tianjin - Hebei Region	Wenzhou City	Zhejiang	Yangtze River Delta Region
Langfang City	Hebei	Beijing - Tianjin - Hebei Region	Jiaxing City	Zhejiang	Yangtze River Delta Region
Hengshui City	Hebei	Beijing - Tianjin - Hebei Region	Huzhou City	Zhejiang	Yangtze River Delta Region
Lanzhou City	Gansu	Lanzhou - Xining Region	Shaoxing City	Zhejiang	Yangtze River Delta Region
Baiyin City	Gansu	Lanzhou - Xining Region	Jinhua City	Zhejiang	Yangtze River Delta Region
Dingxi City	Gansu	Lanzhou - Xining Region	Zhoushan City	Zhejiang	Yangtze River Delta Region
Xining City	Qinghai	Lanzhou - Xining Region	Taizhou City	Zhejiang	Yangtze River Delta Region
Haidong City	Qinghai	Lanzhou - Xining Region	Hefei City	Anhui	Yangtze River Delta Region
Shenyang City	Liaoning	Central - Southern Liaoning	Wuhu City	Anhui	Yangtze River Delta Region

Dalian City	Liaoning	Central - Southern Liaoning	Ma'anshan City	Anhui	Yangtze River Delta Region
Anshan City	Liaoning	Central - Southern Liaoning	Tongling City	Anhui	Yangtze River Delta Region
Fushun City	Liaoning	Central - Southern Liaoning	Anqing City	Anhui	Yangtze River Delta Region
Benxi City	Liaoning	Central - Southern Liaoning	Chuzhou City	Anhui	Yangtze River Delta Region
Yingkou City	Liaoning	Central - Southern Liaoning	Chizhou City	Anhui	Yangtze River Delta Region
Liaoyang City	Liaoning	Central - Southern Liaoning	Xuancheng City	Anhui	Yangtze River Delta
Panjin City	Liaoning	Central - Southern Liaoning	Shenzhen City	Guangdong	Pearl River Delta
Tieling City	Liaoning	Central - Southern Liaoning	Zhuhai City	Guangdong	Pearl River Delta
Yinchuan City	Ningxia	Yellow River - adjacent Area in Ningxia	Foshan City	Guangdong	Pearl River Delta
Shizuishan City	Ningxia	Yellow River - adjacent	Jiangmen City	Guangdong	Pearl River Delta

		Area in Ningxia			
Wuzhong City	Ningxia	Yellow River - adjacent Area in Ningxia	Zhaoqing City	Guangdong	Pearl River Delta
Zhongwei City	Ningxia	Yellow River - adjacent Area in Ningxia	Huizhou City	Guangdong	Pearl River Delta
Guiyang City	Guizhou	Central Guizhou	Dongguan City	Guangdong	Pearl River Delta
Zunyi City	Guizhou	Central Guizhou	Zhongshan City	Guangdong	Pearl River Delta
Anshun City	Guizhou	Central Guizhou	Zhengzhou City	Henan	Central Plains
Bijie City	Guizhou	Central Guizhou	Kaifeng City	Henan	Central Plains
Jinan City	Shandong	Shandong Peninsula	Luoyang City	Henan	Central Plains
Qingdao City	Shandong	Shandong Peninsula	Nanyang City	Henan	Central Plains
Zibo City	Shandong	Shandong Peninsula	Anyang City	Henan	Central Plains
Zaozhuang City	Shandong	Shandong Peninsula	Shangqiu City	Henan	Central Plains
Dongying City	Shandong	Shandong Peninsula	Xinxiang City	Henan	Central Plains
Yantai City	Shandong	Shandong Peninsula	Pingdingshan City	Henan	Central Plains
Weifang City	Shandong	Shandong Peninsula	Xuchang City	Henan	Central Plains

Tai'an City	Shandong	Shandong Peninsula	Zhoukou City	Henan	Central Plains
Weihai City	Shandong	Shandong Peninsula	Jiaozuo City	Henan	Central Plains
Rizhao City	Shandong	Shandong Peninsula	Xinyang City	Henan	Central Plains
Linyi City	Shandong	Shandong Peninsula	Zhumadian City	Henan	Central Plains
Dezhou City	Shandong	Shandong Peninsula	Hebi City	Henan	Central Plains
Liaocheng City	Shandong	Shandong Peninsula	Luohe City	Henan	Central Plains
Heze City	Shandong	Shandong Peninsula	Puyang City	Henan	Central Plains
Taiyuan City	Shanxi	Central Shanxi	Sanmenxia City	Henan	Central Plains
Yangquan City	Shanxi	Central Shanxi	Jiyuan City	Henan	Central Plains
Jinzhong City	Shanxi	Central Shanxi	Changzhi City	Shanxi	Central Plains
Xinzhou City	Shanxi	Central Shanxi	Jincheng City	Shanxi	Central Plains
Lvliang City	Shanxi	Central Shanxi	Yuncheng City	Shanxi	Central Plains
Urumqi City	Xinjiang	Northern Slope of Tianshan Mountains	Xingtai City	Hebei	Central Plains
Karamay City	Xinjiang	Northern Slope of Tianshan Mountains	Handan City	Hebei	Central Plains

Turpan City	Xinjiang	Northern Slope of Tianshan Mountains	Liaocheng City	Shandong	Central Plains
Changji Hui Autonomous Prefecture	Xinjiang	Northern Slope of Tianshan Mountains	Heze City	Shandong	Central Plains
Bortala Mongol Autonomous Prefecture	Xinjiang	Northern Slope of Tianshan Mountains	Huaibei City	Anhui	Central Plains
Yili Kazakh Autonomous Prefecture	Xinjiang	Northern Slope of Tianshan Mountains	Bengbu City	Anhui	Central Plains
Tacheng Prefecture	Xinjiang	Northern Slope of Tianshan Mountains	Suzhou City (Anhui)	Anhui	Central Plains
Shihezi City	Xinjiang	Northern Slope of Tianshan Mountains	Fuyang City	Anhui	Central Plains
			Bozhou City	Anhui	Central Plains

Source: Book[30].

Table S4. Neighbouring province information for each province

Province	Abb.	Neighbor province	Province	Abb.	Neighbor province
Beijing	BJ	Hebei	Hubei	HB	Chongqing
Beijing	BJ	Tianjin	Hubei	HB	Hunan
Tianjin	TJ	Hebei	Hubei	HB	Jiangxi
Tianjin	TJ	Beijing	Hubei	HB	Anhui
Hebei	HE	Liaoning	Hunan	HN	Hubei
Hebei	HE	Inner Mongolia	Hunan	HN	Jiangxi
Hebei	HE	Shanxi	Hunan	HN	Guangdong
Hebei	HE	Henan	Hunan	HN	Guangxi
Hebei	HE	Shandong	Hunan	HN	Guizhou
Hebei	HE	Beijing	Hunan	HN	Chongqing
Hebei	HE	Beijing	Guangdong	GD	Fujian
Shanxi	SX	Inner Mongolia	Guangdong	GD	Jiangxi
Shanxi	SX	Henan	Guangdong	GD	Hunan

Shanxi	SX	Hebei	Guangdong	GD	Guangxi
Shanxi	SX	Shaanxi	Guangdong	GD	Hainan
Inner Mongolia	NM	Heilongjiang	Guangxi Zhuang	GX	Guangdong
Inner Mongolia	NM	Jilin	Guangxi Zhuang	GX	Hunan
Inner Mongolia	NM	Liaoning	Guangxi Zhuang	GX	Guizhou
Inner Mongolia	NM	Hebei	Guangxi Zhuang	GX	Yunnan
Inner Mongolia	NM	Shanxi	Hainan	HI	Guangdong
Inner Mongolia	NM	Shaanxi	Chongqing	CQ	Hubei
Inner Mongolia	NM	Ningxia	Chongqing	CQ	Hunan
Inner Mongolia	NM	Gansu	Chongqing	CQ	Guizhou
Liaoning	LN	Jilin	Chongqing	CQ	Sichuan
Liaoning	LN	Inner Mongolia	Chongqing	CQ	Shaanxi
Liaoning	LN	Hebei	Sichuan	SC	Qinghai
Liaoning	LN	Shandong	Sichuan	SC	Gansu
Jilin	JL	Heilongjiang	Sichuan	SC	Shaanxi

Jilin	JL	Liaoning	Sichuan	SC	Chongqing
Jilin	JL	Inner Mongolia	Sichuan	SC	Guizhou
Heilongjiang	HL	Jilin	Sichuan	SC	Qinghai
Heilongjiang	HL	Inner Mongolia	Sichuan	SC	Tibet
Shanghai	SH	Jiangsu	Guizhou	GZ	Chongqing
Shanghai	SH	Zhejiang	Yunnan	YN	Sichuan
Jiangsu	JS	Shandong	Tibet	XZ	Xinjiang
Jiangsu	JS	Anhui	Shaanxi	SN	Inner Mongolia
Jiangsu	JS	Zhejiang	Guizhou	GZ	Hunan
Jiangsu	JS	Shanghai	Yunnan	YN	Guizhou
Zhejiang	ZJ	Jiangsu	Tibet	XZ	Qinghai
Zhejiang	ZJ	Anhui	Shaanxi	SN	Ningxia
Zhejiang	ZJ	Jiangxi	Guizhou	GZ	Yunnan
Zhejiang	ZJ	Fujian	Guizhou	GZ	Sichuan
Zhejiang	ZJ	Shanghai	Yunnan	YN	Tibet

Anhui	AH	Shandong	Tibet	XZ	Yunnan
Anhui	AH	Jiangsu	Shaanxi	SN	Henan
Anhui	AH	Zhejiang	Guizhou	GZ	Guangxi
Anhui	AH	Jiangxi	Yunnan	YN	Guangxi
Anhui	AH	Hubei	Tibet	XZ	Sichuan
Anhui	AH	Henan	Shaanxi	SN	Hubei
Fujian	FJ	Zhejiang	Shaanxi	SN	Chongqing
Fujian	FJ	Guangdong	Shaanxi	SN	Shanxi
Fujian	FJ	Jiangxi	Shaanxi	SN	Gansu
Jiangxi	JX	Anhui	Shaanxi	SN	Sichuan
Jiangxi	JX	Zhejiang	Gansu	GS	Inner Mongolia
Jiangxi	JX	Fujian	Qinghai	QH	Gansu
Jiangxi	JX	Guangdong	Ningxia	NX	Inner Mongolia
Jiangxi	JX	Hunan	Xinjiang	XJ	Gansu
Jiangxi	JX	Hubei	Gansu	GS	Ningxia

Shandong	SD	Hebei	Qinghai	QH	Sichuan
Shandong	SD	Henan	Ningxia	NX	Gansu
Shandong	SD	Anhui	Xinjiang	XJ	Qinghai
Shandong	SD	Jiangsu	Gansu	GS	Sichuan
Henan	HA	Hebei	Gansu	GS	Qinghai
Henan	HA	Shanxi	Gansu	GS	Xinjiang
Henan	HA	Shaanxi	Gansu	GS	Shaanxi
Henan	HA	Hubei	Qinghai	QH	Xinjiang
Henan	HA	Anhui	Qinghai	QH	Tibet
Henan	HA	Shandong	Ningxia	NX	Shaanxi
Hubei	HB	Henan	Xinjiang	XJ	Tibet
Hubei	HB	Shaanxi			

Table S5. Metric results for PEV and CEV best machine learning models

Type	Test R^2	Train R^2	NMSE	Best model	City Cluster	City number

PEV	0.98	0.99	2.61E-04	BlendTop2(ANN_MLP+SVM)	0	317
	0.96	0.99	1.35E-03	ANN_MLP	1	6
	0.99	0.99	4.58E-05	ANN_MLP	2	43
CEV	0.99	0.99	1.50E-05	ANN_MLP	0	317
	0.87	0.95	8.24E-03	XGB	1	6
	0.95	0.98	1.24E-03	XGB	2	43

Table S6. Market share of 24 types of batteries from 2016 to 2024 under baseline

	BPEV						HPEV						BCEV						HCEV					
yr	LFP	NCM 111	NCM 523	NCM 622	NCM 811	NCA	LFP	NCM 111	NCM 523	NCM 622	NCM 811	NCA	LFP	NCM 111	NCM 523	NCM 622	NCM 811	NCA	LFP	NCM 111	NCM 523	NCM 622	NCM 811	NCA
2016	54%	3%	17%	2%	0%	0%	17%	1%	5%	1%	0%	0%	63%	3%	20%	3%	0%	0%	8%	0%	2%	0%	0%	0%

2017	36%	5%	33%	6%	0%	0%	8%	1%	8%	1%	0%	0%	41%	6%	39%	7%	0%	0%	3%	0%	3%	0%	0%	0%
2018	29%	4%	30%	8%	2%	2%	10%	1%	10%	3%	1%	1%	38%	5%	39%	11%	2%	2%	1%	0%	1%	0%	0%	0%
2019	25%	2%	34%	10%	6%	2%	7%	0%	9%	3%	2%	1%	31%	2%	41%	12%	7%	3%	1%	0%	2%	1%	0%	0%
2020	29%	2%	27%	10%	11%	1%	7%	1%	7%	3%	3%	0%	35%	2%	33%	12%	13%	1%	1%	0%	1%	1%	1%	0%
2021	44%	1%	17%	7%	15%	1%	8%	0%	3%	1%	3%	0%	51%	1%	20%	8%	17%	1%	1%	0%	0%	0%	0%	0%
2022	49%	0%	8%	7%	14%	1%	13%	0%	2%	2%	4%	0%	61%	0%	10%	9%	18%	1%	1%	0%	0%	0%	0%	0%
2023	50%	0%	4%	6%	14%	1%	17%	0%	1%	2%	5%	0%	66%	0%	5%	8%	19%	1%	1%	0%	0%	0%	0%	0%
2024	63%	0%	2%	1%	13%	6%	12%	0%	0%	0%	2%	1%	74%	0%	2%	1%	15%	7%	1%	0%	0%	0%	0%	0%

Source: Journal article[31]; Report[32]. The value is derived by multiplying the 2016–2024 battery-installation shares by the sales shares of electric-vehicle types.

Table S7. Market share of 24 battery types under the NCM-dominated scenarios from 2016 to 2030

	BPEV						HPEV						BCEV						HCEV					
yr	LFP	NCM111	NCM523	NCM622	NCM811	NCA	LFP	NCM111	NCM523	NCM622	NCM811	NCA	LFP	NCM111	NCM523	NCM622	NCM811	NCA	LFP	NCM111	NCM523	NCM622	NCM811	NCA
2016	54%	3%	17%	2%	0%	0%	17%	1%	5%	1%	0%	0%	63%	3%	20%	3%	0%	0%	8%	0%	2%	0%	0%	0%
2017	36%	5%	33%	6%	0%	0%	8%	1%	8%	1%	0%	0%	41%	6%	39%	7%	0%	0%	3%	0%	3%	0%	0%	0%
2018	29%	4%	30%	8%	2%	2%	10%	1%	10%	3%	1%	1%	38%	5%	39%	11%	2%	2%	1%	0%	1%	0%	0%	0%
2019	25%	2%	34%	10%	6%	2%	7%	0%	9%	3%	2%	1%	31%	2%	41%	12%	7%	3%	1%	0%	2%	1%	0%	0%
2020	29%	2%	27%	10%	11%	1%	7%	1%	7%	3%	3%	0%	35%	2%	33%	12%	13%	1%	1%	0%	1%	1%	1%	0%

2021	44%	1%	17%	7%	15%	1%	8%	0%	3%	1%	3%	0%	51%	1%	20%	8%	17%	1%	1%	0%	0%	0%	0%	0%
2022	49%	0%	8%	7%	14%	1%	13%	0%	2%	2%	4%	0%	61%	0%	10%	9%	18%	1%	1%	0%	0%	0%	0%	0%
2023	50%	0%	4%	6%	14%	1%	17%	0%	1%	2%	5%	0%	66%	0%	5%	8%	19%	1%	1%	0%	0%	0%	0%	0%
2024	63%	0%	2%	1%	18%	1%	12%	0%	0%	0%	3%	0%	74%	0%	2%	1%	20%	1%	1%	0%	0%	0%	0%	0%
2025	53%	0%	2%	1%	28%	1%	10%	0%	0%	0%	5%	0%	61%	0%	2%	1%	33%	1%	1%	0%	0%	0%	1%	0%
2026	42%	0%	2%	1%	39%	1%	8%	0%	0%	0%	7%	0%	49%	0%	2%	1%	45%	1%	1%	0%	0%	0%	1%	0%
2027	32%	0%	2%	1%	49%	1%	6%	0%	0%	0%	9%	0%	37%	0%	2%	1%	57%	1%	1%	0%	0%	0%	1%	0%

2028	21%	0%	2%	1%	60%	1%	4%	0%	0%	0%	11%	0%	25%	0%	2%	1%	70%	1%	0%	0%	0%	0%	1%	0%
2029	11%	0%	2%	1%	70%	1%	2%	0%	0%	0%	13%	0%	12%	0%	2%	1%	82%	1%	0%	0%	0%	0%	1%	0%
2030	0%	0%	2%	1%	81%	1%	0%	0%	0%	0%	15%	0%	0%	0%	2%	1%	94%	1%	0%	0%	0%	0%	2%	0%

* The NCM dominant scenario assumes zero installed capacity for LFP batteries by 2030.

Table S8. Service life and weight of 24 types of batteries

BPEV Battery	LFP	NCM111	NCM523	NCM622	NCM811	NCA
Lifespan (yr)	9.5	8.5	8	7.5	7	7.5
Weight (kg)	350	349	303	305	479	208
BCEV Battery	LFP	NCM111	NCM523	NCM622	NCM811	NCA
Lifespan (yr)	10.5	9.5	9	8.5	8	8.5
Weight (kg)	790	762	783	833	846	926

HPEV Battery	LFP	NCM111	NCM523	NCM622	NCM811	NCA
Lifespan (yr)	6	5	4.5	4	4	5
Weight (kg)	357	333	278	250	227	278
HCEV Battery	**LFP**	**NCM111**	**NCM523**	**NCM622**	**NCM811**	**NCA**
Lifespan (yr)	6.5	5.5	5	4.5	4.5	5.5
Weight (kg)	160	170	174	188	190	204

Source: Journal article[16,33]; Thesis[34]; Report [35].

Table S9. The metal weight of lithium-ion battery packs (kg/kWh)

Metal	LFP	NCA	NMC 111	NMC532	NMC 622	NMC 811
lithium	9.50E-02	1.02E-01	1.41E-01	1.36E-01	1.18E-01	1.00E-01
nickel	0.00E+00	6.72E-01	3.51E-01	5.08E-01	5.31E-01	6.00E-01
cobalt	0.00E+00	1.27E-01	3.52E-01	2.04E-01	1.78E-01	7.50E-02
manganese	0.00E+00	0.00E+00	3.28E-01	2.85E-01	1.66E-01	7.00E-02

Source: Journal article[33,36].

Table S10. Predictions of EOL power batteries volume from 2024 to 2030 by other studies

Reference	Unit	2024	2025	2026	2027	2028	2029	2030
Wu et al. (2020) [16]	10^3 t	249.92	307.07	375.49	450.43	531.45	616.86	708.67
Yang et al. (2024) [33]	10^3 t	399	542.2	697.4	891.3	1165.6	1508.1	1925.5
Zhang et al. (2025)[37]	10^3 t	330	360	640	760	1030	1720	1991
China Business Industry Research Institute[38]	10^3 t	600	1040	1400	1800	2300	2900	3500
CABRCA[39]	10^3 t	170	240	337	465	627	825	1058
Wang and Yu (2021)[40]	10^4 t	105-135	135-173	175-225	231-297	287-369	288-432	340-511
GGII [41]	10^3 t	-	960	-	-	-	-	-
China Business Industry Research Institute [38]	GWh	75	130	175	225	288	363	438
CABRCA [39]	GWh	20.2	30.1	44	62.5	86.1	114.8	148.7
GGII [41]	GWh	-	137.4	-	-	-	-	-

Table S11. Comparison of predictive results with EOL battery from other studies (10^3 t)

Year	This study	Zhang et al. (2025) [37]	Tan et al. (2023) [42]	Wang and Yu (2021) [40]	Wu et al. (2020)[16]	Yang et al. (2024)[33]	Dagong Global Credit Rating Co. Ltd. and Ministry of Commerce and Industry (2025)[43]
2020	98.9	180	269.3	225	112.8	75.3	47
2021	209	250	395.4	450	155.9	131.5	55
2022	330	260	507.4	585	186.1	199.7	94
2023	441	340	619.4	684	211.4	293.3	168

Table S12. Inventory data of crushing and decomposition of EOL LFP battery

Flow		**Amount**	**Unit**	**Provider**
Input	EOL NCM battery	1.00E+04	t	EOL NCM battery
	Limestone	6.00E+01	t	modified Solvay process, Hou's process | soda ash, dense | Cutoff, S
	soda ash	1.00E+01	t	modified Solvay process, Hou's process | soda ash, dense | Cutoff, S
	Water	4.06E+05	m^3	water production, underground water with chemical treatment | tap water | Cutoff, S

	Natural gas	5.42E+00	TJ	heat and power co-generation, natural gas, 50kW electrical, lean burn | heat, central or small-scale, natural gas | Cutoff, S
	Electricity	1.01E+07	kWh	Electricity Structure by Province
Output	Cathode material	4.84E+03	t	Cathode material
	Calcium phosphate	5.10E+01	t	Calcium phosphate
	Circulating water	4.06E+05	t	Circulating water
	Copper foil	1.39E+03	t	Copper foil
	Non-methane hydrocarbon	5.50E+00	t	Non-methane hydrocarbon
	Plastic and Container	1.93E+03	t	Plastic and Container
	Aluminium	5.81E+02	t	Aluminium
	Waste water	2.00E+01	t	Waste water
	Ash	8.76E+01	t	Ash
	Calcium fluoride waste	3.85E+01	t	Calcium fluoride waste
	Solid Waste	1.14E+03	t	Solid Waste

	hydrogen fluoride	6.58E-01	t	hydrogen fluoride
	Particulate	4.40E-01	t	> 2.5 um and < 10um

Source: Report[44].

Table S13. Inventory data of crushing and decomposition of EOL NCM battery

Flow		Amount	Unit	Provider
Input	EoL LFP battery	1.00E+04	t	EoL LFP battery
	Natural gas	5.42E+00	TJ	heat and power co-generation, natural gas, 50kW electrical, lean burn | heat, central or small-scale, natural gas | Cutoff, S
	Lime	6.00E+01	t	liquid packaging board production | lime, from liquid packaging board production | Cutoff, S
	Soda ash, dense	1.00E+01	t	modified Solvay process, Hou's process | soda ash, dense | Cutoff, S
	Tap water	4.06E+05	kg	tap water production, underground water with chemical treatment | tap water | Cutoff, S
	Electricity	3.63E+07	MJ	Electricity Structure by Province

Output	Ash	8.76E+01	t	Ash
	Calcium fluoride waste	3.85E+01	t	Calcium fluoride waste
	Calcium phosphate	5.10E+01	t	Calcium phosphate
	Cathode material	4.84E+03	t	Cathode material, LFP, for lithium-ion battery
	Circulating water	4.06E+05	t	
	Copper foil	1.39E+03	t	
	Hydrogen fluoride	6.58E-01	t	
	Non-methane hydrocarbon	5.50E+00	t	
	Particulate matter	4.40E-01	t	> 2.5 um and < 10um
	Waste plastic packaging	1.93E+03	t	Waste Plastic Packaging
	Aluminum	5.81E+02	t	Powdered Aluminum
	Solid waste	1.14E+03	t	Solid Waste
	Waste water	2.00E+01	t	untreated, slightly organic and anorganic contaminated, at waste water treatment plant, industrial waste water according to the Directive 91/271/EEC concerning urban waste water treatment

Source: Report[44].

Table S14. Inventory data of the low emission pyro-hydrometallurgy for EOL NCM batteries

Flow		Amount	Unit	Provider
Input	**Eol NCM battery**	**1.00E+03**	**kg**	**EOL NCM battery**
	Steam	1.36E+03	MJ	steam production, as energy carrier, in chemical industry | heat, from steam, in chemical industry | Cutoff, S
	Hydrochloric acid	2.33E+02	kg	market for hydrochloric acid, without water, in 30% solution state | hydrochloric acid, without water, in 30% solution state | Cutoff, S
	Hydrogen peroxide	3.28E+01	kg	market for hydrogen peroxide, without water, in 50% solution state | hydrogen peroxide, without water, in 50% solution state | Cutoff, S
	Laterite, mineral	1.70E+02	kg	laterite quarry operation | laterite, mineral | Cutoff, S
	Lime	4.90E+01	kg	lime production, hydrated, packed | lime, hydrated, packed | Cutoff, S
	Limestone	1.70E+02	kg	limestone quarry operation | limestone, unprocessed | Cutoff, S
	Petroleum coke	1.87E+02	kg	petroleum coke production, petroleum refinery operation | petroleum coke | Cutoff, S
	Tap water	1.40E+01	kg	tap water production, underground water with chemical treatment | tap water | Cutoff, S

Output	Carbon dioxide	4.17E+02	kg	Carbon dioxide
	Lithium carbonate	1.18E+02	kg	Lithium carbonate
	Ternary precursor	3.13E+02	kg	Ternary precursor

Source: Journal article[45].

Table S15. Inventory data of high emission pyrometallurgy for EOL NCM batteries

Flow		**Amount**	**Unit**	**Provider**
Input	**EoL NCM battery**	**1.E+03**	**kg**	**EoL NCM battery**
	Natural gas	7.E+03	MJ	natural gas, burned in micro gas turbine, 100kWe | heat, central or small-scale, natural gas | Cutoff, S
	Hydrogen peroxide	9.E+01	kg	hydrogen peroxide production, product in 50% solution state | hydrogen peroxide, without water, in 50% solution state | Cutoff, S
	Limestone	1.E+03	kg	market for limestone, crushed, for mill | limestone, crushed, for mill | Cutoff, S
	Lithium carbonate	2.E+02	kg	lithium carbonate production, from spodumene | lithium carbonate | Cutoff, S

	Process-specific burdens, slag landfill	8.E+04	kg	process-specific burdens, slag landfill | process-specific burdens, slag landfill | Cutoff, S
	Sodium hydroxide	3.E+03	kg	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, S
	Sulfuric acid	4.E+03	kg	sulfuric acid production | sulfuric acid | Cutoff, S
	Electricity	5.E+03	MJ	Electricity Structure by Province
Output	Aluminum	1.E+02	kg	Aluminum
	Carbon dioxide	1.E+04	kg	carbon dioxide
	Copper	1.E+03	kg	Copper
	Iron	9.E+02	kg	Iron
	Nickel and Cobalt Alloy	1.E+03	kg	Nickel and Cobalt Alloy

Source: journal article[46].

Table S16. Inventory data of high emission hydrometallurgy for EOL LFP batteries

Flow		Amount	Unit	Provider
Input	**EOL LFP battery**	**1.00E+03**	**kg**	**EOL LFP battery**

Steam	3.83E+02	MJ	steam production, as energy carrier, in chemical industry | heat, from steam, in chemical industry | Cutoff, S
Heavy fuel oil	4.04E+01	kg	heavy fuel oil production, petroleum refinery operation | heavy fuel oil | Cutoff, S
Hydrochloric acid	7.92E+03	kg	zirconium and hafnium tetrachloride production, from zircon | hydrochloric acid, without water, in 30% solution state | Cutoff, S
Hydrogen peroxide	1.32E+03	kg	hydrogen peroxide production, product in 50% solution state | hydrogen peroxide, without water, in 50% solution state | Cutoff, S
Light fuel oil	2.47E+01	kg	light fuel oil production, petroleum refinery operation | light fuel oil | Cutoff, S
Magnesium chloride	1.80E+00	kg	
Petroleum coke	2.04E-01	kg	petroleum coke production, petroleum refinery operation | petroleum coke | Cutoff, S
Potash salt	8.47E-01	kg	potash salt production | potash salt | Cutoff, S
Silicon	4.15E+01	kg	
Sodium carbonate	1.21E+03	kg	sodium carbonate
Sodium chloride	9.88E-01	kg	Sodium chloride

	Sodium hydroxide	5.63E+03	kg	chlor-alkali electrolysis, membrane cell | sodium hydroxide, without water, in 50% solution state | Cutoff, S
	Spent activated carbon	2.04E-01	kg	spent activated carbon, granular, Recycled Content cut-off | spent activated carbon, granular | Cutoff, S
	Tap water	2.22E+03	kg	tap water production, underground water with chemical treatment | tap water | Cutoff, S
	Electricity	5.50E+00	kWh	Electricity Structure by Province
output	Hazardous waste	2.60E+04	kg	hazardous waste (unspecified)
	Iron phosphate	-3.30E+03	kg	Iron phosphate
	Lithium carbonate	-1.18E+03	kg	lithium carbonate
	Polypropylene diaphragm	-3.52E+02	kg	Polypropylene Diaphragm
	Steel	-3.99E+02	kg	Scrap Steel
	Aluminum	-7.08E+02	kg	Secondary Aluminum
	Copper	-8.09E+02	kg	Secondary copper

Source: Journal article[47].

Table S17. Inventory data of high emission hydrometallurgy for EOL NCM batteries

Flow		Amount	Unit	Provider
Input	**Eol NCM battery**	**1.00E+03**	**kg**	**EoL NCM battery**
	P507	1.81E-01	kg	P507 production | P507 | Cutoff, S
	Nano-alumina	5.06E+01	kg	ammonia production, steam reforming, liquid | ammonia, anhydrous, liquid | Cutoff, S
	P204	4.70E-01	kg	P207 production | P507 | Cutoff, S
	Hydrochloric acid	2.89E+03	kg	hydrochloric acid production, from the reaction of hydrogen with chlorine | hydrochloric acid, without water, in 30% solution state | Cutoff, S
	Kerosene	1.20E+00	kg	kerosene production, petroleum refinery operation | kerosene | Cutoff, S
	Sodium chloride	8.13E+03	kg	sodium chloride production, powder | sodium chloride, powder | Cutoff, S
	Sodium hydroxide	1.06E+02	kg	chlor-alkali electrolysis, membrane cell | sodium hydroxide, without water, in 50% solution state | Cutoff, S
	Sodium sulfide	1.20E+00	kg	sodium sulfide production | sodium sulfide | Cutoff, S
	Steam	1.45E+03	kg	nitric acid production, product in 50% solution state | steam, in chemical industry | Cutoff, S
	Sulfuric acid	1.53E+02	kg	smelting of copper concentrate, sulfide ore | sulfuric acid | Cutoff, S

	Water	1.00E+04	kg	tap water production, underground water with disinfection | tap water | Cutoff, S
	Electricity	2.24E+03	kWh	Electricity Structure by Province
Output	Ammonia	1.08E+01	g	ammonia
	Bod5	4.39E+02	g	Biological Oxygen Demand
	Cathode material	1.51E+02	kg	NMC, for lithium-ion battery
	Cobalt	4.82E+00	g	cobalt
	Cod, chemical oxygen demand	1.24E+03	g	Chemical Oxygen Demand
	Dust	5.30E+01	g	Dust
	Fluorosulfuric acid	4.82E+00	g	fluorosulfuric acid
	Hydrogen fluoride	5.30E+01	g	hydrogen fluoride
	Hydrogen sulfide	2.41E+00	g	hydrogen sulfide
	Lithium	4.80E+02	g	lithium
	Manganese (ii)	6.02E+00	g	manganese
	Nickel (ii)	6.02E+00	g	nickel

Oxirane, reaction products with ammonia, distn. Residues	7.23E+01	g	oxirane, reaction products with ammonia, dust. residues
Suspended solids, unspecified	1.49E+04	g	Suspended solids, unspecified

Source: journal article[48].

Table S18. Inventory data of low emission hydrometallurgy for EOL LFP batteries

Flow		Amount	Unit	Provider
Input	**EoL LFP battery**	**1.00E+03**	**kg**	
	Natural gas	2.31E+01	MJ	heat and power co-generation, natural gas, 500kW electrical, lean burn | heat, district or industrial, natural gas | Cutoff, S
	Hydrogen peroxide	4.92E+01	kg	hydrogen peroxide production, product in 50% solution state | hydrogen peroxide, without water, in 50% solution state | Cutoff, S
	Lime	4.72E+00	kg	lime production, hydrated, packed | lime, hydrated, packed | Cutoff, S
	Soda ash	1.71E+02	kg	soda production, solvay process | soda ash, light | Cutoff, S
	Sodium chloride	4.43E+00	kg	market for sodium chloride, powder | sodium chloride, powder | Cutoff, S

	Sodium hydroxide	7.03E+00	kg	chlor-alkali electrolysis, mercury cell | sodium hydroxide, without water, in 50% solution state | Cutoff, S
	Sulfuric acid	2.25E+02	kg	sulfuric acid production | sulfuric acid | Cutoff, S
	Water	2.09E+03	kg	water production, underground water with chemical treatment | water | Cutoff, S
	Electricity	1.34E+03	MJ	Electricity Structure by Province
Output	Ammonia	1.31E-03	kg	ammonia
	Cod	1.30E-02	kg	chemical oxygen demand
	Dust	1.25E-01	kg	Dust
	Fluorosulfuric acid	1.91E-02	kg	fluorosulfuric acid
	Fluorosulfuric acid	1.91E-01	kg	fluorosulfuric acid
	Lithium carbonate	1.26E+02	kg	lithium carbonate
	Residue to landfill	7.97E+02	kg	Residue to landfill
	Sodium sulfate	2.22E+02	kg	Sodium sulfate
	Suspended solids	2.89E-03	kg	Suspended solids
	Waste water	6.48E+01	m3	Waste water

Source: journal artice[45]

Table S19. Inventory data of low emission hydrometallurgy for EOL LFP batteries

Flow		Amount	Unit	Provider
Input	EoL NCM battery	1.00E+03	kg	
	P507	6.47E-02	kg	P507 production | P507 | Cutoff, S
	Steam	1.91E+03	MJ	steam production, as energy carrier, in chemical industry | heat, from steam, in chemical industry | Cutoff, S
	Hydrochloric acid	2.59E+02	kg	hydrochloric acid production, from the reaction of hydrogen with chlorine | hydrochloric acid, without water, in 30% solution state | Cutoff, S
	Kerosene	3.24E-01	kg	kerosene production, petroleum refinery operation | kerosene | Cutoff, S
	Soda ash, light	2.24E+01	kg	soda production, solvay process | soda ash, light | Cutoff, S
	Sodium hydroxide	6.54E+02	kg	chlor-alkali electrolysis, membrane cell | sodium hydroxide, without water, in 50% solution state | Cutoff, S
	Sulfuric acid	9.12E+02	kg	sulfuric acid production | sulfuric acid | Cutoff, S
	Water	6.47E+03	kg	tap water production, underground water with chemical treatment | tap water | Cutoff, S

	Electricity	2.54E+02	kWh	Electricity Structure by Province
Output	Ammonia	3.68E-03	kg	ammonia
	Cod	5.54E-02	kg	chemical oxygen demand
	Cobalt sulfate	1.75E+02	kg	cobalt sulfate
	Dust	1.35E-01	kg	Dust
	Hydrochloric acidsodium salts	7.09E-02	kg	hydrochloric acid, reaction products with aniline and nitrobenzene, sulfonated, sodium salts
	Hydrochloric acid	7.09E-01	kg	hydrochloric acid, reaction products with aniline and nitrobenzene, sulfonated, sodium salts
	Lithium carbonate	2.09E+02	kg	lithium carbonate
	Manganese sulfate	1.79E+02	kg	manganese sulfate
	Nickel sulfate	1.79E+02	kg	nickel sulfate
	Non-methane volatile organic compounds	6.07E-02	kg	non-methane volatile organic compounds
	Residue to landfill	6.13E+02	kg	Residue to landfill
	Sodium chloride	2.80E+02	kg	sodium chloride, powder

	Sodium sulfate	5.00E+02	kg	sodium sulfate, anhydrite
	Sulfuric acid	3.57E-02	kg	sulfuric acid, c9 alkyl esters, sodium salts
	Sulfuric acid	3.57E-01	kg	sulfuric acid, c9 alkyl esters, sodium salts
	Suspended solids	2.76E-02	kg	Suspended solids, unspecified
	Waste water	1.85E+02	kg	waste water - untreated, slightly organic and anorganic contaminated, at waste water treatment plant, industrial waste water according to the Directive 91/271/EEC concerning urban waste water treatment

Source: journal artice[49]

Table S20. Inventory data of medium emission pyrometallurgy for EOL LFP batteries

Flow		Amount	Unit	Provider
input	**EoL LFP battery**	**1.00E+03**	**kg**	**EoL LFP battery**
	Natural gas	6.84E+03	MJ	heat and power co-generation, natural gas, 50kW electrical, lean burn | heat, central or small-scale, natural gas | Cutoff, S
	Hydrogen peroxide	2.50E+02	kg	hydrogen peroxide production, product in 50% solution state | hydrogen peroxide, without water, in 50% solution state | Cutoff, S

	Limestone	1.36E+03	kg	limestone production, crushed, for mill | limestone, crushed, for mill | Cutoff, S
	Process-specific burdens	7.86E+04	kg	market for process-specific burdens, slag landfill | process-specific burdens, slag landfill | Cutoff, S
	Sodium hydroxide	1.36E+03	kg	chlor-alkali electrolysis, diaphragm cell | sodium hydroxide, without water, in 50% solution state | Cutoff, S
	Sulfuric acid	4.39E+03	kg	primary zinc production from concentrate | sulfuric acid | Cutoff, S
	Electricity	6.41E+03	MJ	Electricity Structure by Province
Output	Aluminum slag	1.40E+02	kg	
	Carbon dioxide	1.03E+04	kg	
	Copper Scrap	9.80E+02	kg	
	Iron	9.10E+02	kg	

Source: journal artice[50,51]

Table S21. Inventory data of medium emission hydrometallurgy for EOL NCM batteries

Flow	Amount	Unit	Provider

Input	**EoL NCM battery**	**1.00E+03**	**kg**	**EoL NCM battery**
	Ammonia	1.12E+02	kg	ammonia production, steam reforming, liquid | ammonia, anhydrous, liquid | Cutoff, S
	P507	2.00E+00	kg	P507 production | P507 | Cutoff, S
	Natural gas	2.33E+03	MJ	heat production, natural gas, at boiler condensing modulating <100kW | heat, central or small-scale, natural gas | Cutoff, S
	Hydrochloric acid, 30%	4.00E+01	kg	hydrochloric acid production, from the reaction of hydrogen with chlorine | hydrochloric acid, without water, in 30% solution state | Cutoff, S
	Hydrogen peroxide, 50%	3.66E+02	kg	hydrogen peroxide production, product in 50% solution state | hydrogen peroxide, without water, in 50% solution state | Cutoff, S
	Kerosene	4.89E+00	kg	kerosene production, petroleum refinery operation | kerosene | Cutoff, S
	Lithium carbonate	1.21E+02	kg	Lithium carbonate production;Lithium carbonate;Brine
	Sodium chloride, powder	2.10E+01	kg	market for sodium chloride, powder | sodium chloride, powder | Cutoff, S
	Sodium hydroxide, 50%	1.87E+03	kg	chlor-alkali electrolysis, diaphragm cell | sodium hydroxide, without water, in 50% solution state | Cutoff, S
	Sulfuric acid	1.10E+03	kg	smelting of copper concentrate, sulfide ore | sulfuric acid | Cutoff, S

	Water	1.40E+04	kg	tap water production, underground water with disinfection | tap water | Cutoff, S
	Electricity	1.01E+03	MJ	Electricity Structure by Province
Output	Ammonia nitrogen	5.99E+01	kg	Ammonia nitrogen
	Carbon dioxide	6.73E+01	kg	carbon dioxide
	Copper scrap	9.99E+01	kg	Copper Scrap
	Lithium carbonate	3.00E+02	kg	lithium carbonate
	Nickel	4.00E+00	kg	nickel
	Packaging waste, plastic	4.00E+01	kg	Packaging waste, plastic
	Aluminum	5.99E+01	kg	aluminum
	Residue to landfill	3.51E+02	kg	Residue to landfill
	Waste steel wire	1.80E+02	kg	Waste steel wire
	Waste water	9.99E+03	kg	untreated, slightly organic and anorganic contaminated, at waste water treatment plant, industrial waste water according to the Directive 91/271/EEC concerning urban waste water treatment

Source: journal artice[48]

Table S22. Inventory data of secondary utilization for EOL LFP batteries

Flow		Amount	Unit	**Provider**
Input	**EOL LFP battery**	**1.00E+00**	**kg**	
	Cables	1.21E-02	kg	cable production, unspecified | cable, unspecified | Cutoff, S
	Casing	3.23E-02	kg	wire drawing, steel | wire drawing, steel | Cutoff, S
	BMS	8.08E-03	kg	Battery management system production; Battery management system; Electronic components
	Nickel	4.04E-03	kg	
	Electricity	6.74E-02	kWh	Electricity Structure by Province
Output	LFP battery for ESS	1.00E+00	kg	LFP battery for energy storage
	Scrap metal casing	3.57E-02	kg	Scrap metal casing
	Scrap plastic	2.56E-03	kg	Scrap plastic
	Scrap cables	4.85E-03	kg	Scrap cables

Scrap BMS circuit boards	2.43E-03	kg	Scrap BMS circuit boards

Source: report[52].

Table S23. GWP of ignoring the differences in provincial electricity and technology

Province	Ignoring process variations	Ignoring power variations	This study
Guangdong	1.55E+10	3.64E+10	2.14E+10
Jiangsu	8.45E+09	2.39E+10	1.49E+10
Zhejiang	7.15E+09	1.96E+10	9.01E+09
Beijing	3.31E+09	1.62E+10	7.15E+09
Shanghai	4.61E+09	1.51E+10	9.46E+09
Henan	6.65E+09	1.49E+10	9.54E+09
Shandong	7.67E+09	1.45E+10	9.00E+09
Hebei	4.94E+09	1.34E+10	7.83E+09
Sichuan	4.29E+09	1.30E+10	4.86E+09
Hubei	3.13E+09	9.27E+09	3.35E+09
Anhui	3.78E+09	8.72E+09	5.26E+09
Shaanxi	2.79E+09	8.57E+09	4.87E+09
Yunnan	2.00E+09	7.95E+09	3.40E+09
Hunan	2.80E+09	7.91E+09	3.11E+09
Guangxi	2.88E+09	7.71E+09	4.13E+09
Fujian	2.95E+09	7.35E+09	3.88E+09
Hainan	1.77E+09	7.27E+09	4.83E+09
Tianjin	2.15E+09	6.62E+09	4.39E+09
Liaoning	2.09E+09	6.56E+09	4.01E+09
Shanxi	3.39E+09	6.12E+09	4.34E+09

Heilongjiang	1.50E+09	5.35E+09	4.01E+09
Chongqing	1.80E+09	5.22E+09	2.09E+09
Xinjiang	1.28E+09	5.03E+09	3.22E+09
Jiangxi	1.77E+09	4.76E+09	1.75E+09
Guizhou	2.05E+09	4.72E+09	2.79E+09
Inner Mongolia	1.61E+09	2.96E+09	2.51E+09
Jilin	1.21E+09	2.50E+09	1.78E+09
Gansu	7.50E+08	1.87E+09	9.54E+08
Qinghai	2.25E+08	1.16E+09	4.67E+08
Ningxia	4.99E+08	1.06E+09	6.57E+08
Tibet	6.46E+07	4.03E+08	1.25E+08
Total	1.05E+11	2.86E+11	1.59E+11

*In the 'Ignoring process variations' scenario, the processes used are all 'Medium emission'; in the 'Ignoring power variations' scenario, calculations are based on the national average values from the ecoinvent 3.9 database.

Table S24. Dynamic Life of Electric Vehicles from 2016 to 2030

Year	PEV lifespan (yr)	CEV lifespan (yr)	Year of lifespan
2016	8	5	2016-2017
2018	9	6	2018-2019
2020	10	7	2020-2022

2023	11	8	2023-2024
2025	12	9	2025-2027
2028	13	10	2028-2029
2030	15	12	2030

Source: Journal[16]

Table S25. Types and units of environmental impact indicators

Impact category group	Name of the impact category	Indicators	Unit
Depletion of abiotic resources	Depletion of abiotic resources—elements, ultimate reserves	ADP element	kg Sb -eq.
	Depletion of abiotic resources—fossil fuels	ADP fossil	MJ
Climate change	Global Warming Potential	GWP	kg CO_2-eq.
Acidification	Acidification potential	AP	kg SO_2-eq.

Eutrophication	Eutrophication potential	EP	kg PO^4 eq.
Photochemical oxidation	Photochemical oxidation potential	POCP	kg C_2H_4 eq.
Human toxicity	Human toxicity potential	HTP	kg 1.4-DB eq.
Ozone layer depletion	Ozone layer depletion potential	ODPP	kg CFC-11 eq
Ecotoxicity	Terrestrial ecotoxicity potential	TETP	kg 1.4-DB eq.
	Marine aquatic ecotoxicity potential	MAETP	kg 1.4-DB eq.

Source: Journal article[53]

Table S26. Non-formal recycling enterprises of varying scales across Chinese provinces

year	province	Abb.	Micro number	Medium number
2020	Anhui	AH	8	0
2020	Beijing	BJ	1	0
2020	Fujian	FJ	8	2
2020	Gansu	GS	4	0
2020	Guangdong	GD	15	1
2020	Guangxi Zhuang	GX	1	1
2020	Guizhou	GZ	2	1
2020	Hainan	HI	2	0
2020	Hebei	HE	11	1
2020	Henan	HA	10	5
2020	Heilongjiang	HL	0	0
2020	Hubei	HB	7	1
2020	Hunan	HN	11	3
2020	Jilin	JL	2	0
2020	Jiangsu	JS	9	5
2020	Jiangxi	JX	7	1
2020	Liaoning	LN	4	1
2020	Inner Mongolia	NM	2	0
2020	Ningxia	NX	0	1
2020	Qinghai	QH	1	2
2020	Shandong	SD	7	3

2020	Shanxi	SX	2	0
2020	Shaanxi	SN	15	6
2020	Shanghai	SH	0	1
2020	Sichuan	SC	3	1
2020	Tianjin	TJ	0	0
2020	Tibet	XZ	0	0
2020	Xinjiang	XJ	7	1
2020	Yunnan	YN	3	4
2020	Zhejiang	ZJ	5	0
2020	Chongqing	CQ	0	2
2021	Anhui	AH	79	22
2021	Beijing	BJ	2	1
2021	Fujian	FJ	47	14
2021	Gansu	GS	18	6
2021	Guangdong	GD	48	5
2021	Guangxi	GX	22	9
2021	Guizhou	GZ	20	3
2021	Hainan	HI	71	7
2021	Hebei	HE	14	7
2021	Henan	HA	89	18
2021	Heilongjiang	HL	5	0
2021	Hubei	HB	9	1
2021	Hunan	HN	17	7
2021	Jilin	JL	21	0

2021	Jiangsu	JS	50	24
2021	Jiangxi	JX	23	5
2021	Liaoning	LN	10	7
2021	Inner Mongolia	NM	7	3
2021	Ningxia	NX	2	1
2021	Qinghai	QH	20	4
2021	Shandong	SD	37	10
2021	Shanxi	SX	7	1
2021	Shaanxi	SN	90	32
2021	Shanghai	SH	2	1
2021	Sichuan	SC	36	3
2021	Tianjin	TJ	1	0
2021	Tibet	XZ	3	1
2021	Xinjiang	XJ	28	7
2021	Yunnan	YN	47	15
2021	Zhejiang	ZJ	19	4
2021	Chongqing	CQ	20	6
2022	Anhui	AH	139	139
2022	Beijing	BJ	16	16
2022	Fujian	FJ	63	63
2022	Gansu	GS	44	44
2022	Guangdong	GD	177	177
2022	Guangxi Zhuang	GX	24	24
2022	Guizhou	GZ	100	100

2022	Hainan	HI	137	137
2022	Hebei	HE	53	53
2022	Henan	HA	137	137
2022	Heilongjiang	HL	8	8
2022	Hubei	HB	73	73
2022	Hunan	HN	109	109
2022	Jilin	JL	47	47
2022	Jiangsu	JS	104	104
2022	Jiangxi	JX	43	43
2022	Liaoning	LN	14	14
2022	Inner Mongolia	NM	20	20
2022	Ningxia	NX	9	9
2022	Qinghai	QH	15	15
2022	Shandong	SD	89	89
2022	Shanxi	SX	27	27
2022	Shaanxi	SN	119	119
2022	Shanghai	SH	9	9
2022	Sichuan	SC	39	39
2022	Tianjin	TJ	3	3
2022	Tibet	XZ	9	9
2022	Xinjiang	XJ	52	52
2022	Yunnan	YN	118	118
2022	Zhejiang	ZJ	41	41
2022	Chongqing	CQ	44	44

2023	Anhui	AH	159	26
2023	Beijing	BJ	54	11
2023	Fujian	FJ	67	29
2023	Gansu	GS	78	12
2023	Guangdong	GD	190	38
2023	Guangxi Zhuang	GX	16	12
2023	Guizhou	GZ	59	16
2023	Hainan	HI	98	3
2023	Hebei	HE	225	63
2023	Henan	HA	80	19
2023	Heilongjiang	HL	10	2
2023	Hubei	HB	66	17
2023	Hunan	HN	101	28
2023	Jilin	JL	11	4
2023	Jiangsu	JS	123	30
2023	Jiangxi	JX	36	9
2023	Liaoning	LN	12	7
2023	Inner Mongolia	NM	10	3
2023	Ningxia	NX	8	1
2023	Qinghai	QH	13	3
2023	Shandong	SD	47	13
2023	Shanxi	SX	27	9
2023	Shaanxi	SN	103	33
2023	Shanghai	SH	4	6

2023	Sichuan	SC	29	5
2023	Tianjin	TJ	1	1
2023	Tibet	XZ	4	2
2023	Xinjiang	XJ	37	13
2023	Yunnan	YN	123	17
2023	Zhejiang	ZJ	45	12
2023	Chongqing	CQ	40	8
2024	Anhui	AH	264	42
2024	Beijing	BJ	65	10
2024	Fujian	FJ	148	22
2024	Gansu	GS	41	10
2024	Guangdong	GD	261	34
2024	Guangxi Zhuang	GX	127	15
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2024	Hubei	HB	96	20
2024	Hunan	HN	124	29
2024	Jilin	JL	43	9
2024	Jiangsu	JS	167	52
2024	Jiangxi	JX	48	14
2024	Liaoning	LN	18	17

2024	Inner Mongolia	NM	27	8
2024	Ningxia	NX	15	5
2024	Qinghai	QH	18	4
2024	Shandong	SD	29	23
2024	Shanxi	SX	32	18
2024	Shaanxi	SN	52	14
2024	Shanghai	SH	25	9
2024	Sichuan	SC	94	13
2024	Tianjin	TJ	10	7
2024	Tibet	XZ	10	1
2024	Xinjiang	XJ	65	15
2024	Yunnan	YN	213	16
2024	Zhejiang	ZJ	89	17
2024	Chongqing	CQ	61	17

Source: Chinese Enterprises Data Website[54].

Table S27. Comparison of GWP (100a) Values for CML and IPCC

Process	CML (kg CO_2-eq. / kg)	IPCC (kg CO_2-eq. / kg)
Low emission pyro-hydrometallurgy for NCM	0.49	0.50
Low-emission hydrometallurgy for NCM	1.48	1.49
Low-emission hydrometallurgy for LFP	0.31	0.31
Medium-emission hydrometallurgy for NCM	4.64	4.68
Medium-emission pyrometallurgy for LFP	4.09	4.11
High-emission hydrometallurgy for NCM	7.74	7.8
High-emission hydrometallurgy for LFP	12.14	12.22
High-emission pyrometallurgy for NCM	8.07	8.12

Table S28. Referred database about the electricity generation by different energy sources.

Energy	Database
Coal	Ecoinvent: electricity production, natural gas, combined cycle power plant | electricity, high voltage | Cutoff, S - CN-*(Corresponding to the databases of 31 provinces in Chinese mainland)*
Natural gas combined cycle	Ecoinvent: electricity production, natural gas, combined cycle power plant | electricity, high voltage | Cutoff, S - CN-*(Corresponding to the databases of 31 provinces in Chinese mainland)*
Natural gas combustion turbine	Ecoinvent: electricity production, natural gas, conventional power plant | electricity, high voltage | Cutoff, S - CN-*(Corresponding to the databases of 31 provinces in Chinese mainland)*

Biogas	Ecoinvent: heat and power co-generation, biogas, gas engine | electricity, high voltage | Cutoff, S - RoW
Hydro	Ecoinvent: electricity production, hydro, reservoir, non-alpine region | electricity, high voltage | Cutoff, S - RoW
	Ecoinvent: electricity production, hydro, run-of-river | electricity, high voltage | Cutoff, S - CN- *(Corresponding to the databases of 31 provinces in Chinese mainland)*
Nuclear power	Ecoinvent: electricity production, nuclear, boiling water reactor | electricity, high voltage | Cutoff, U-RoW
	Ecoinvent: electricity production, nuclear, pressure water reactor | electricity, high voltage | Cutoff, S - CN- *(Corresponding to the databases of 31 provinces in Chinese mainland)*
Pumped hydro storage	Ecoinvent: electricity production, hydro, pumped storage | electricity, high voltage | Cutoff, S - CN- *(Corresponding to the databases of 31 provinces in Chinese mainland)*
Wind	Ecoinvent: electricity production, wind, <1MW turbine, onshore | electricity, high voltage | Cutoff, S - CN- *(Corresponding to the databases of 31 provinces in Chinese mainland)*
Photovoltaic	Ecoinvent: photovoltaic plant construction, 570kWp, multi-Si, on open ground | photovoltaic plant, 570kWp, multi-Si, on open ground | Cutoff, U-Global
Lithium battery	Ecoinvent: battery production, Li-ion, rechargeable, prismatic | battery, Li-ion, rechargeable, prismatic | Cutoff, U-Global

Source: Journal article[55].

Table S29. Summary of thermodynamic limit calculation results

Process	T(°C)	ΔH (MJ/kg)	ΔQ (MJ/kg)	Qutil (MJ/kg)	Limit (MJ/kg)	Actual (MJ/kg)
High-emission pyrometallurgy for NCM	1500	–12.85	21.53	12.85	**8.68**	12.08
Medium-emission pyrometallurgy for LFP	1500	–10.55	19.89	10.55	**9.34**	13.25
Low emission pyro-hydrometallurgy for NCM	1500/ 80	–3.12	11.24	2.9	**8.34**	8.01
High-emission hydrometallurgy for NCM	80	1.89	1.25	0	**3.14**	78.96
Medium-emission hydrometallurgy for NCM	80	0.95	0.68	0	**1.63**	3.34
Low-emission hydrometallurgy for NCM	80	0.77	0.53	0	**1.3**	2.82
High-emission hydrometallurgy for LFP	80	2.45	1.02	0	**3.47**	20.2
Low-emission hydrometallurgy for LFP	80	0.51	0.44	0	**0.95**	1.36

Table S30. Environmental impact during the transportation stage

Impact category	Unit	Result
Abiotic depletion	kg Sb eq	4.79E-07

Abiotic depletion (fossil fuels)	MJ	2.148231
Acidification	kg SO_2 eq	0.000314
Eutrophication	kg PO_4--- eq	7.9E-05
Fresh water aquatic ecotox.	kg 1,4-DB eq	0.031637
Global warming (GWP100a)	kg CO_2 eq	0.150244
Human toxicity	kg 1,4-DB eq	0.0658
Marine aquatic ecotoxicity	kg 1,4-DB eq	62.38766
Ozone layer depletion (ODP)	kg CFC-11 eq	2.03E-09
Photochemical oxidation	kg C_2H_4 eq	2.26E-05
Terrestrial ecotoxicity	kg 1,4-DB eq	0.000184

Table S31. Comparison of unit environmental impact results calculated by other studies

Study	Processes (Functional unit: 1 kg EOL battery)	ADP fossil	AP	EP	GWP 100a	HTP	POCP
Tian et al. (2024)[53]	Hydrometallurgical processes for LFP	1.00E-05	9.34E-03	1.55E-03	2.64	1.72	4.05E-04
Chen et al. (2025)[56]	Hydrometallurgical processes for LFP	-	-	-	1.59	-	-
	Hydrometallurgical processes for NCM	-	-	-	7.62	-	-
Chen et al., (2023)[57]	Hydrometallurgical processes for LFP	-	-	-	2.28	-	-

	Direct recycling-A	-	-	-	8.78	-	-
	Direct recycling-B	-	-	-	1.06	-	-
	Direct recycling-C	-	-	-	7.5	-	-
Chen et al., (2023)[57]	Hydrometallurgical processes for NCM	-	-	-	8.7	-	-
	Direct recycling-B	-	-	-	1.54	-	-
	Direct recycling-C	-	-	-	5.34	-	-
Chen et al. (2022)[58]	Pyrometallurgical processes for NCM	-	-	-	1.15	-	-
	Hydrometallurgical processes for NCM	-	-	-	0.6	-	-
	Direct recycling for NCM	-	-	-	0.82	-	-

Table S32. Metal recovery rates of eight recycling processes

processes	lithium	nickel	cobalt	manganese
high-emission hydrometallurgy for LFP	0.80	0.0	0.0	0.0
high-emission hydrometallurgy for NCM	0.80	0.90	0.90	0.90
high-emission pyrometallurgy for NCM	0.80	0.90	0.90	0.90
medium-emission	0.85	0.0	0.0	0.0

processes	lithium	nickel	cobalt	manganese
pyrometallurgy for LFP				
medium-emission hydrometallurgy for NCM	0.85	0.95	0.95	0.95
low-emission hydrometallurgy for LFP	0.90	0.0	0.0	0.0
low-emission hydrometallurgy for NCM	0.90	0.98	0.98	0.98
low-emission pyro-hydrometallurgy for NCM	0.91	0.985	0.985	0.985

Supplementary Figures

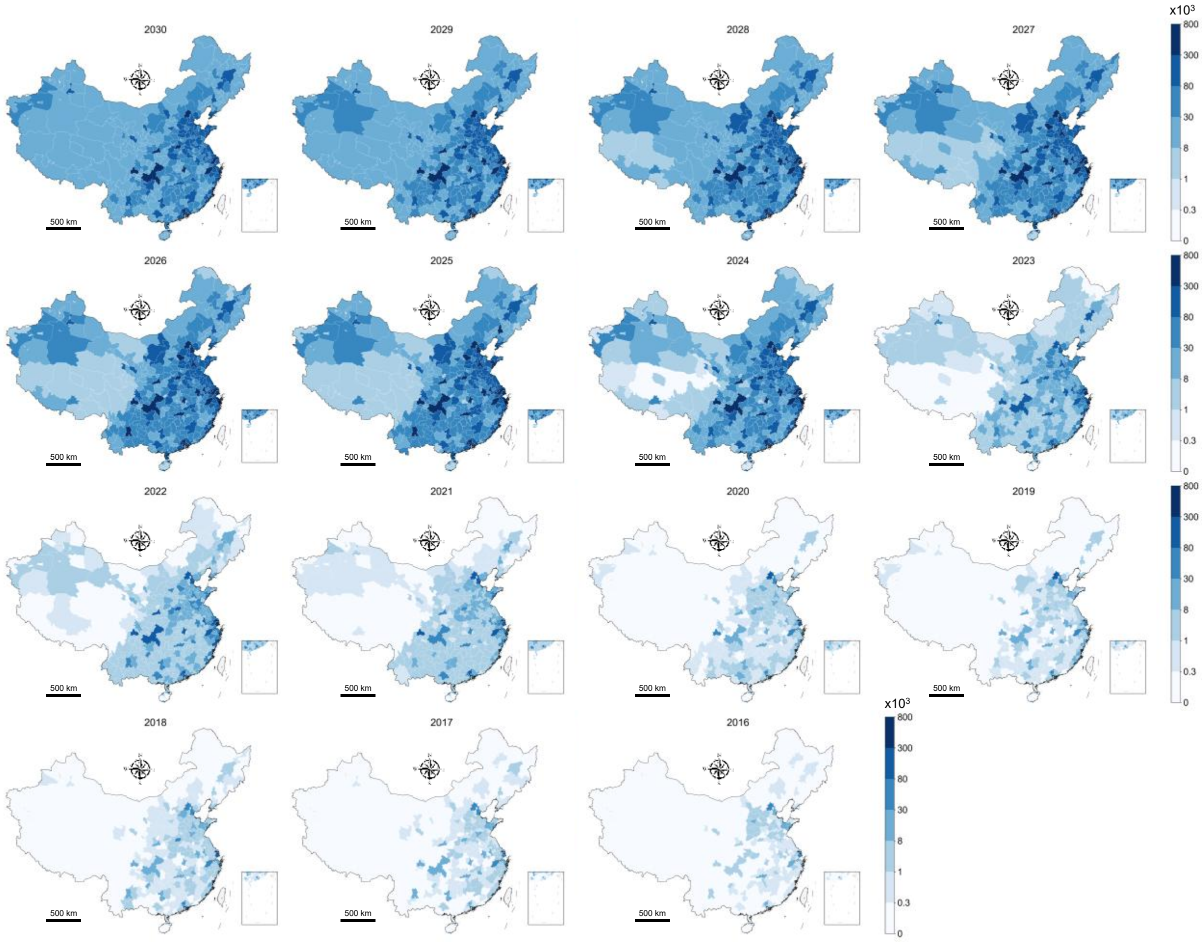


Figure S1. Urban distribution map of passenger electric vehicle insurance volume in China from 2016 to 2030 (Unit: 10^3 vehicles)

* The annual figures represent the number of newly insured electric vehicles in each city, not the cumulative total. Map data are based on standard map data approved under GS(2023)2767. Inset maps show the national map of China, including the South China Sea islands, for geographic reference.

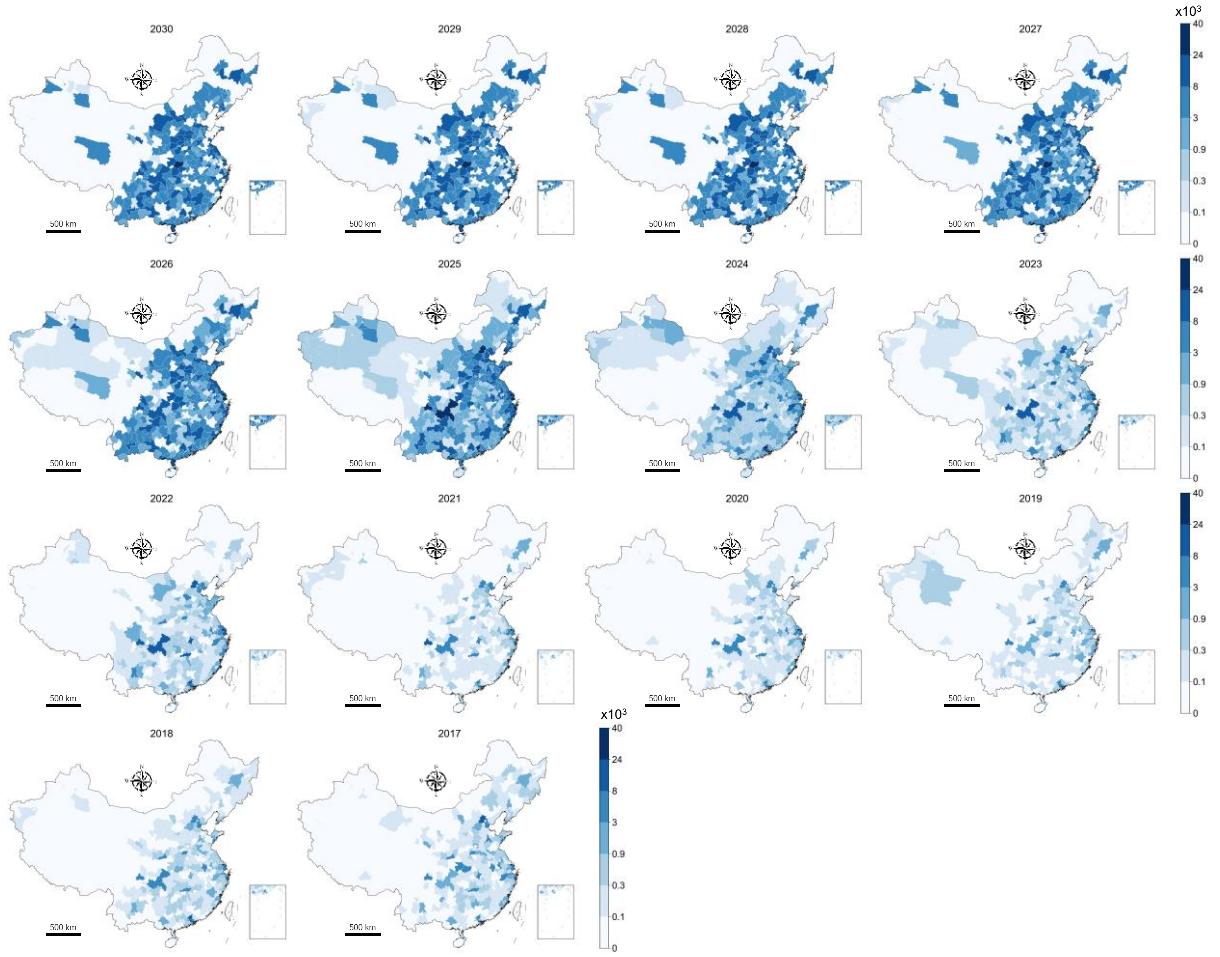
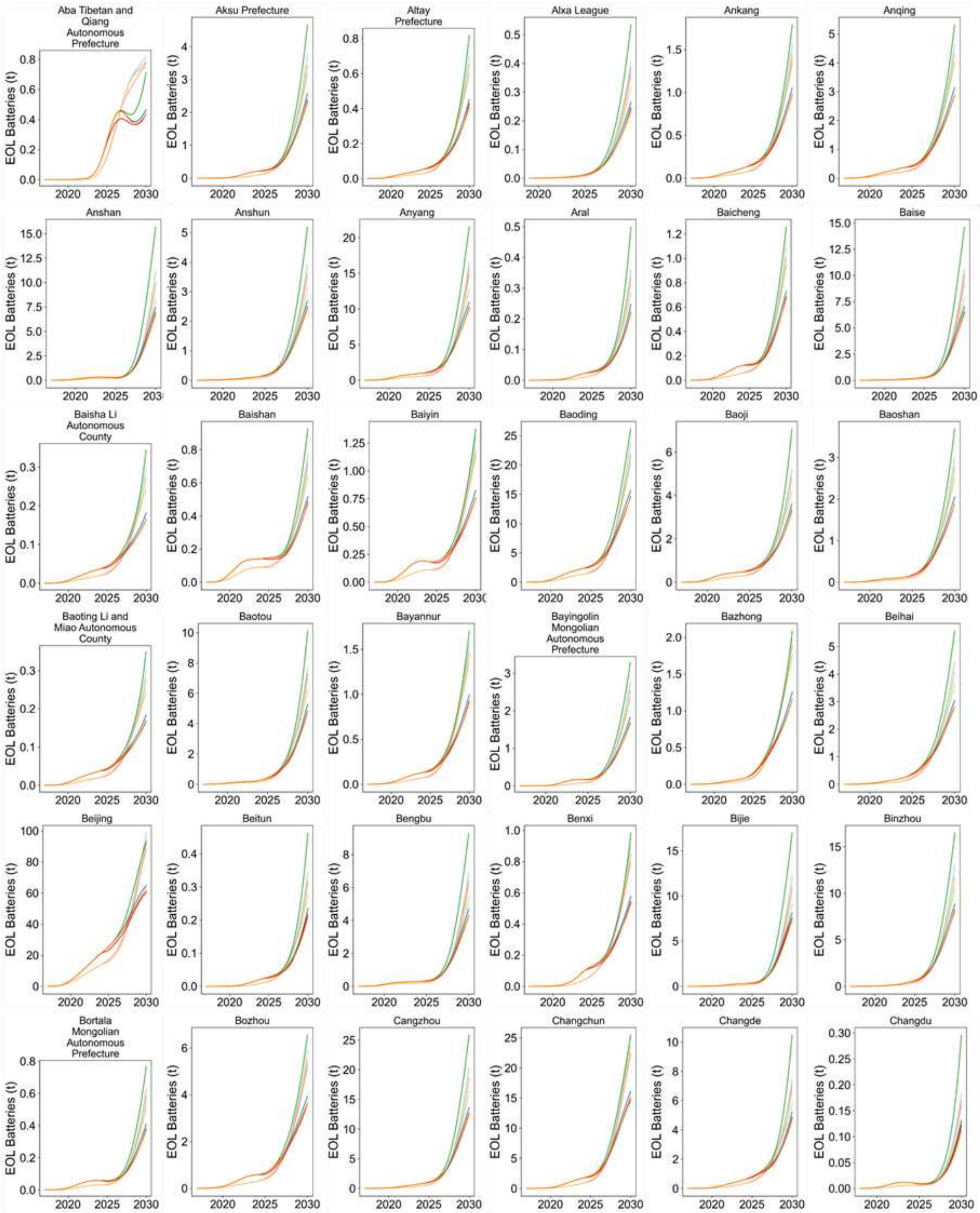


Figure S2. Urban distribution map of commercial electric vehicle insurance volume in China from 2017 to 2030 (Unit: 10^3 vehicles)

* The annual figures represent the number of newly insured electric vehicles in each city, not the cumulative total. Map data are based on standard map data approved under GS(2023)2767. Inset maps show the national map of China, including the South China Sea islands, for geographic reference.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Bayingolin Mongolian Autonomous Prefecture
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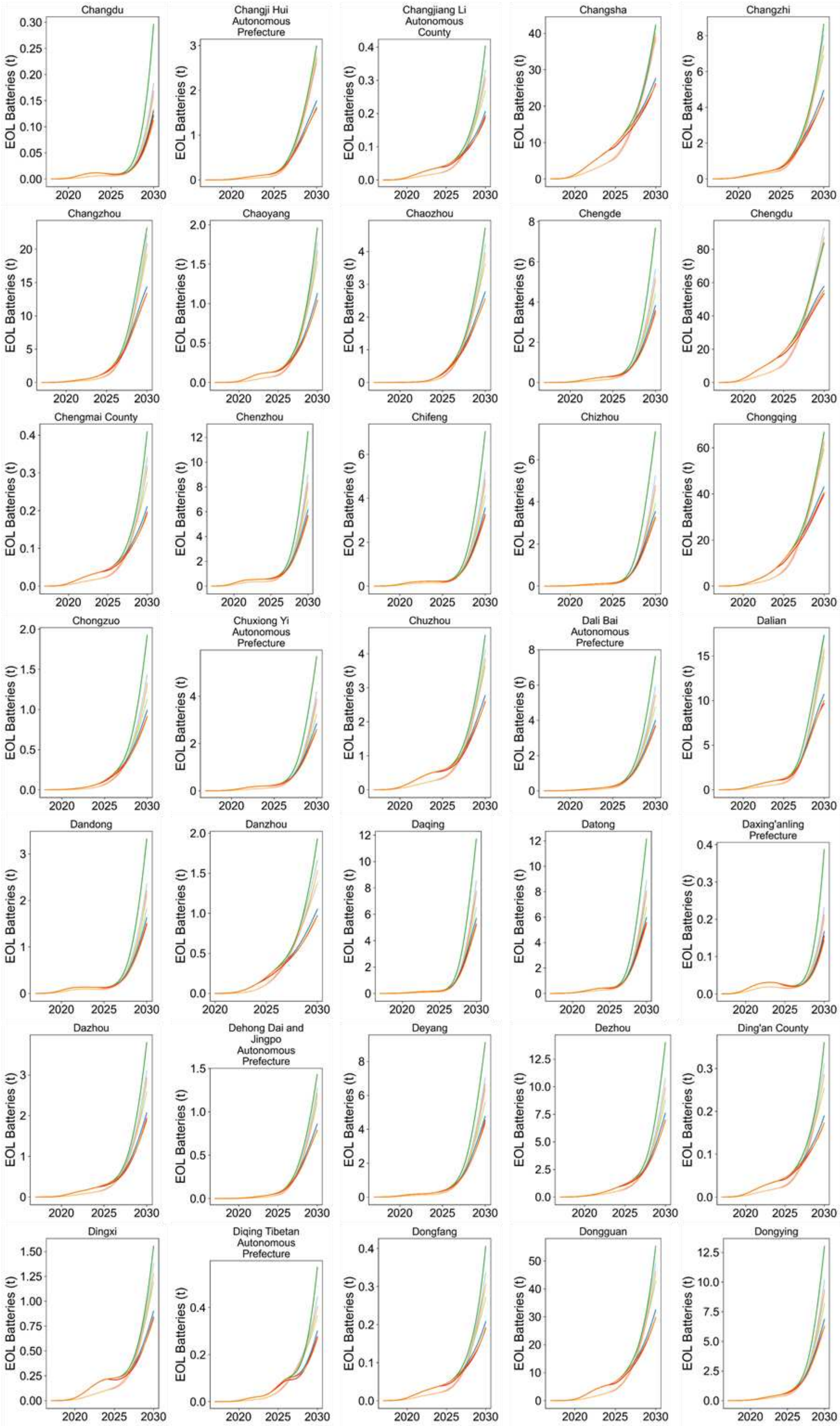

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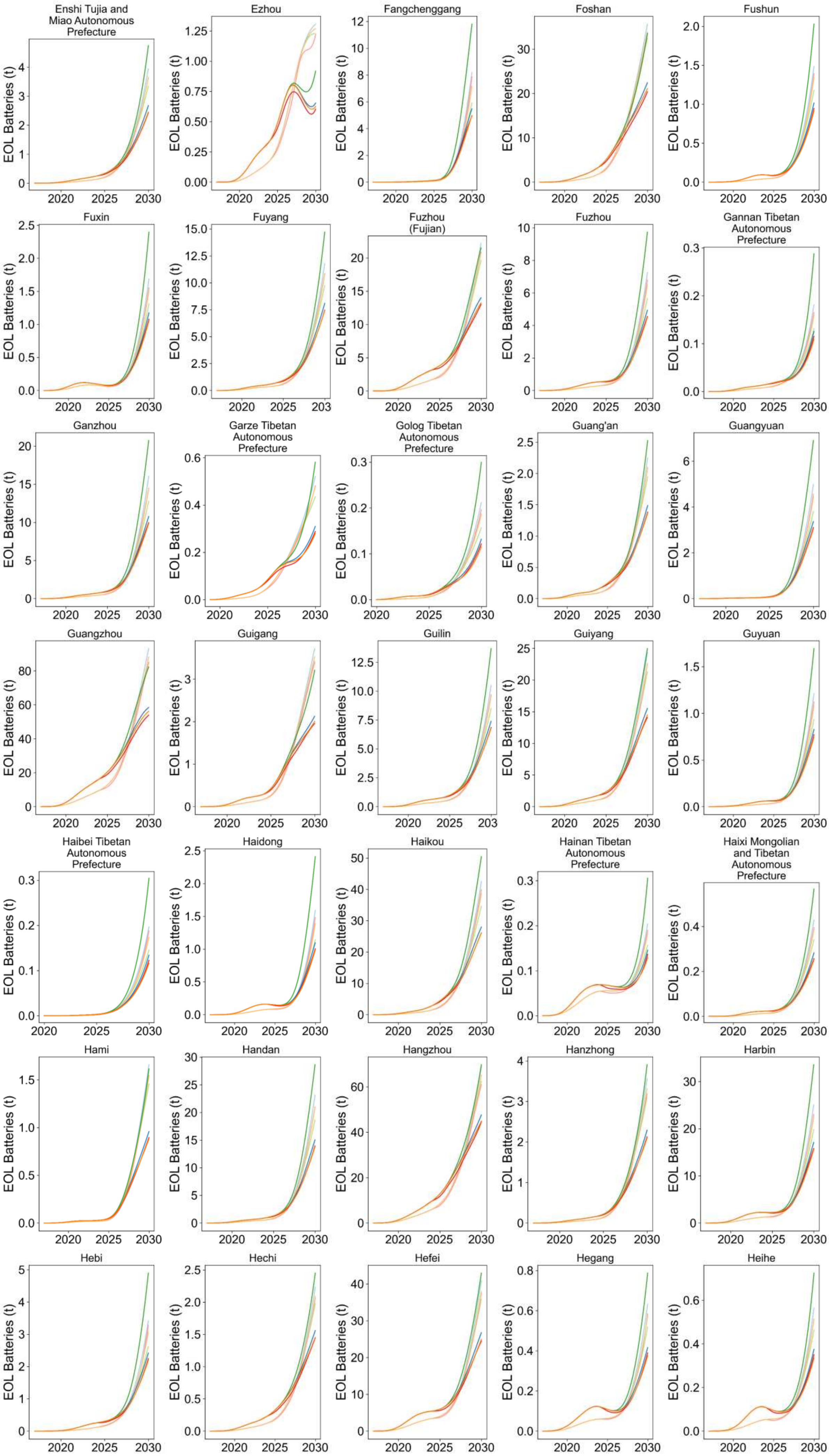

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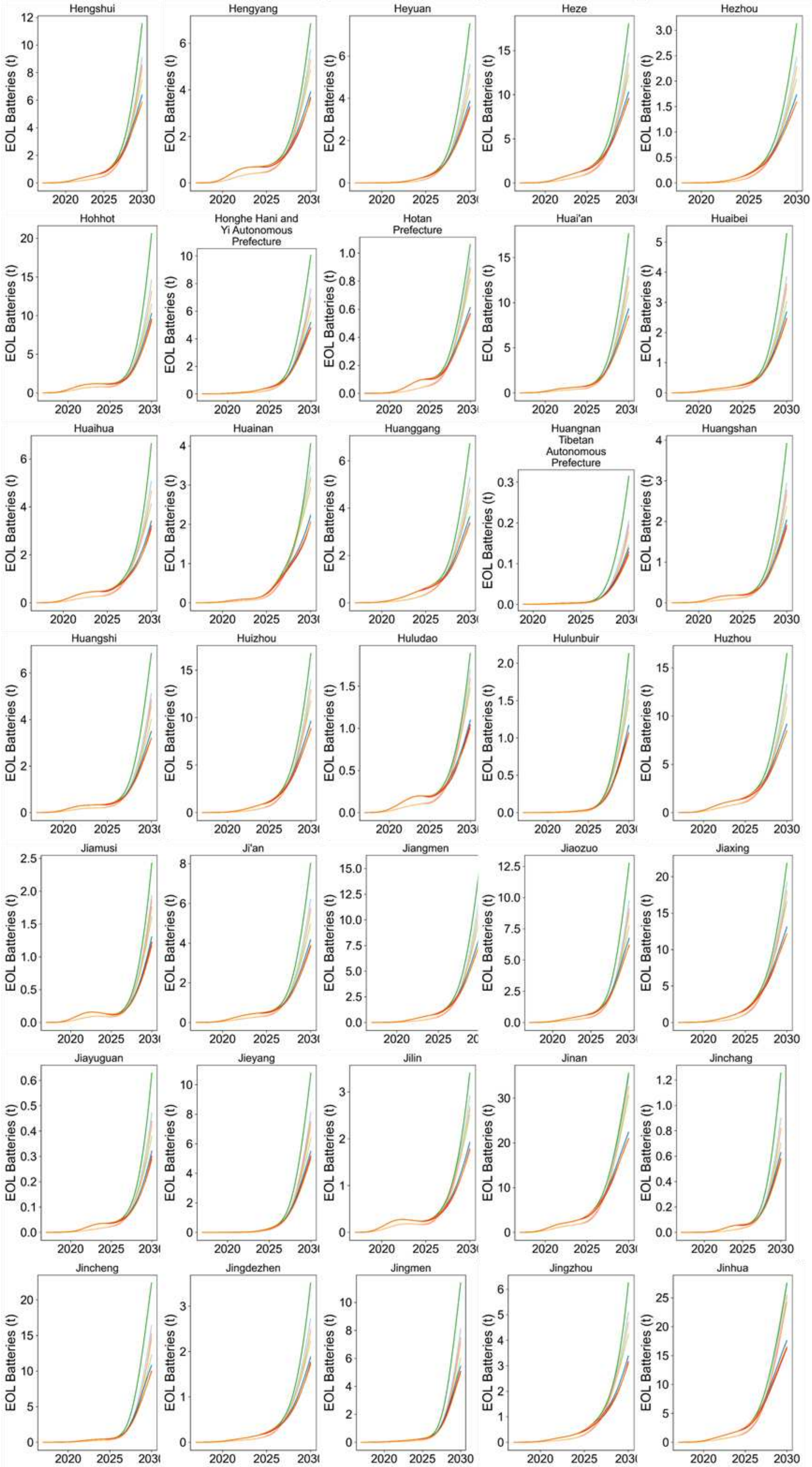
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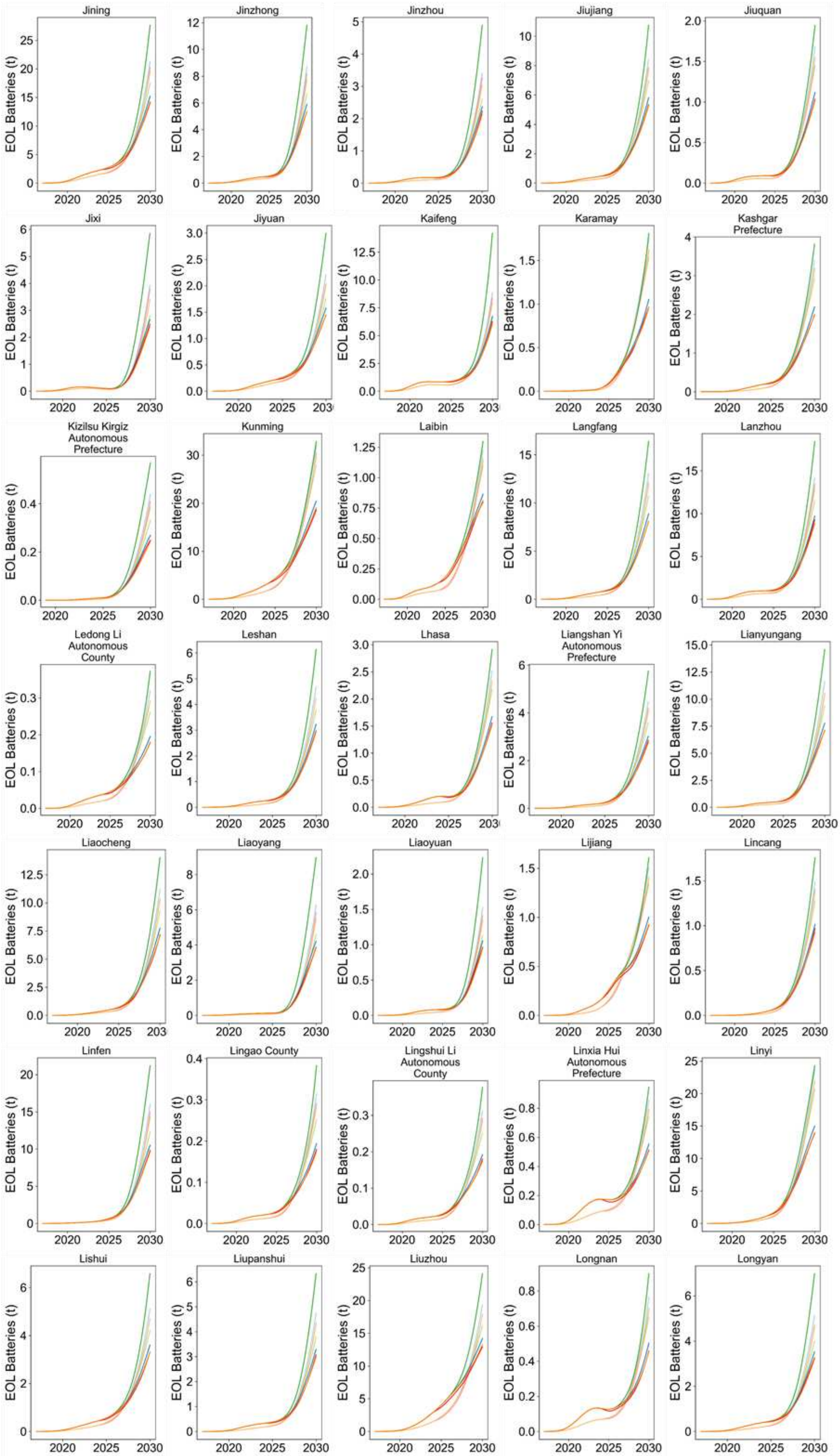

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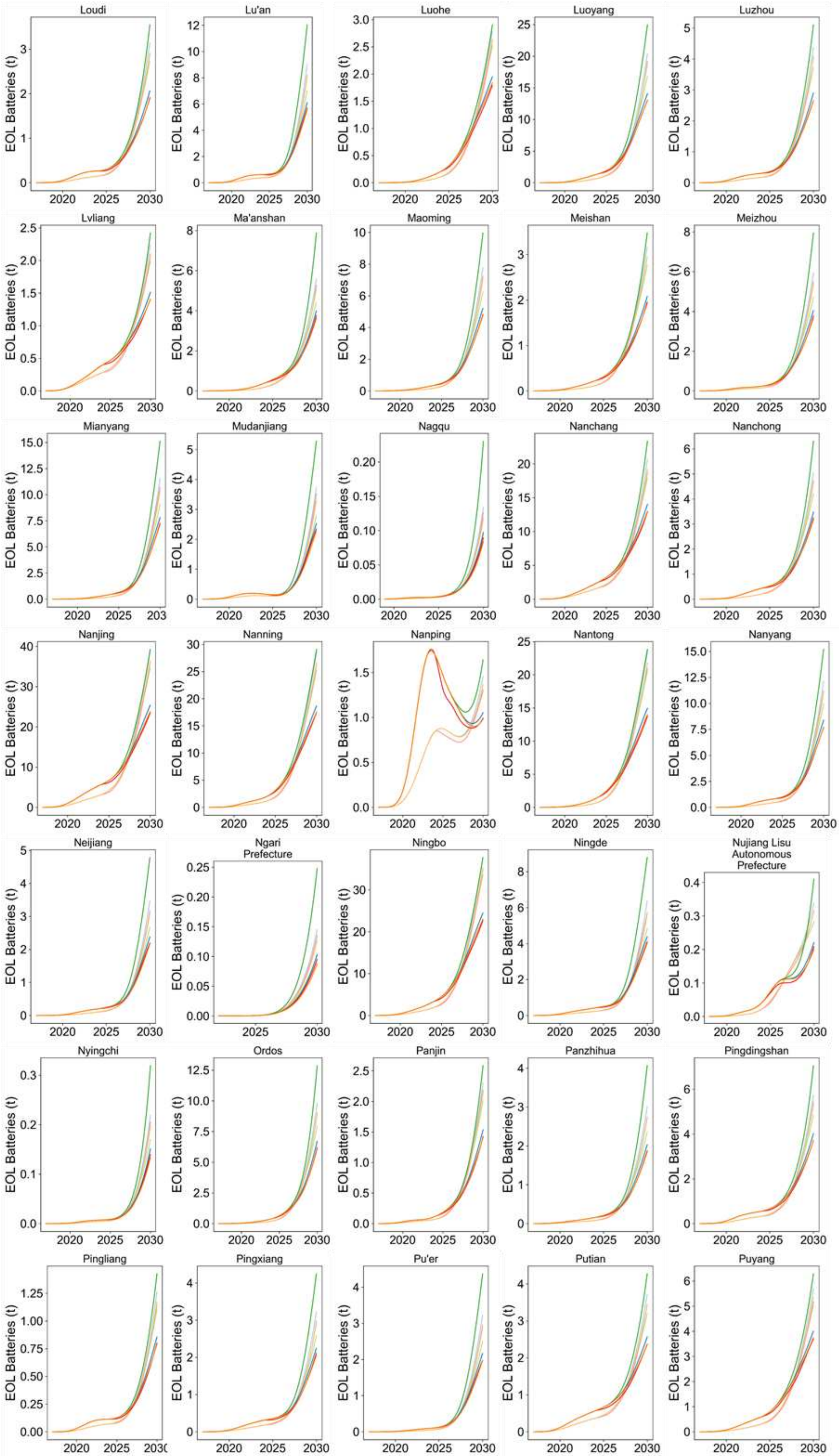

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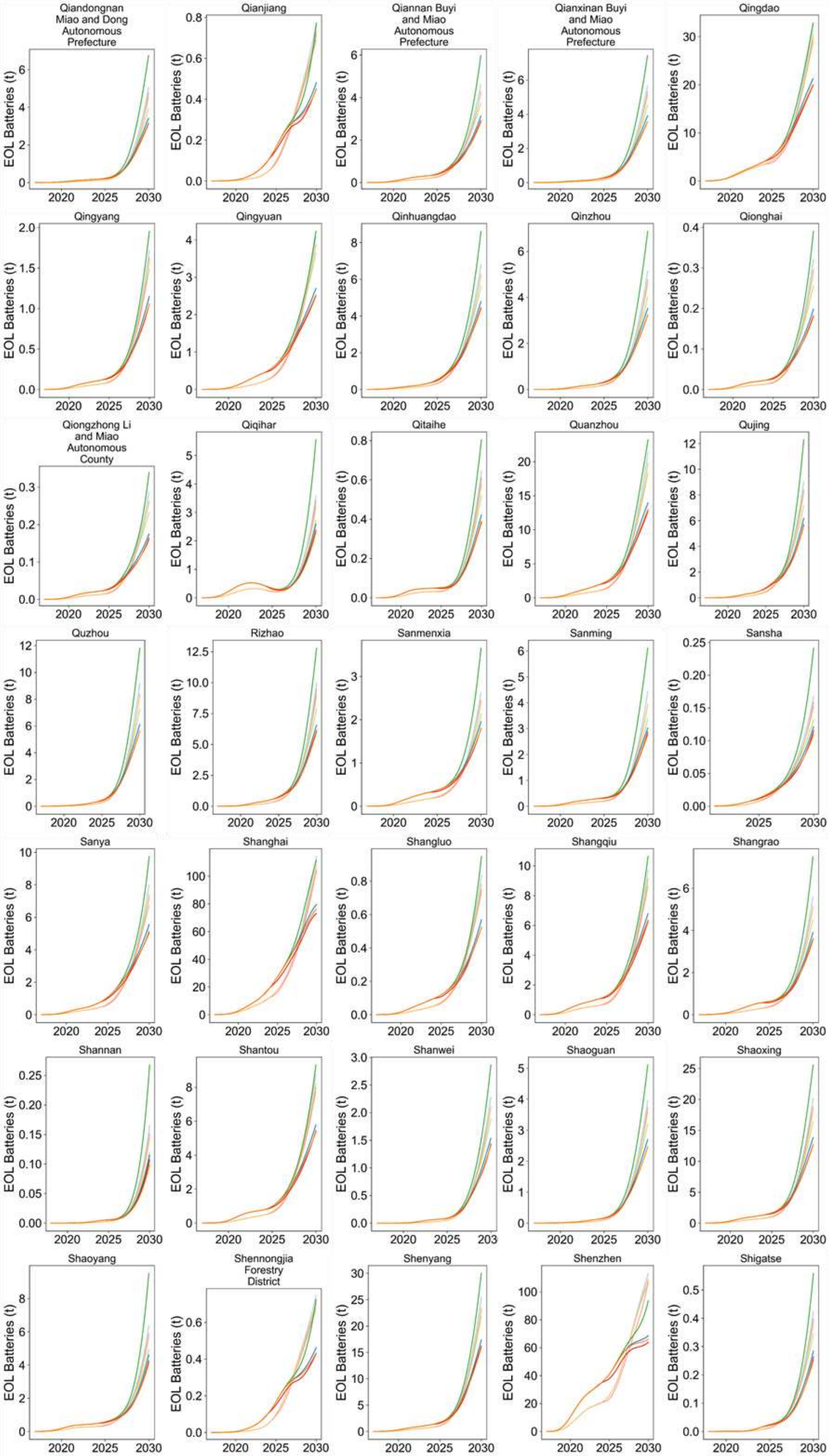
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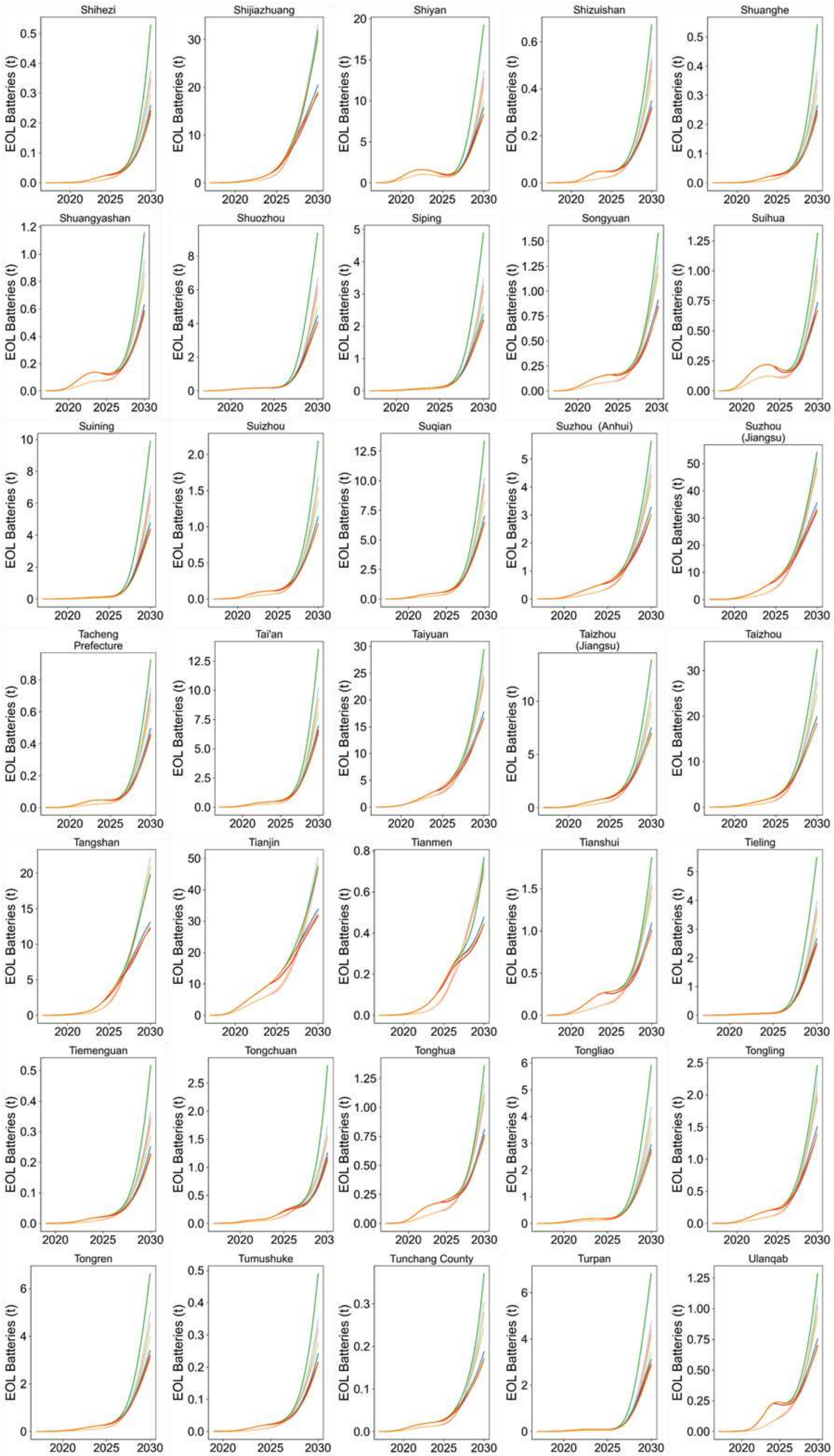
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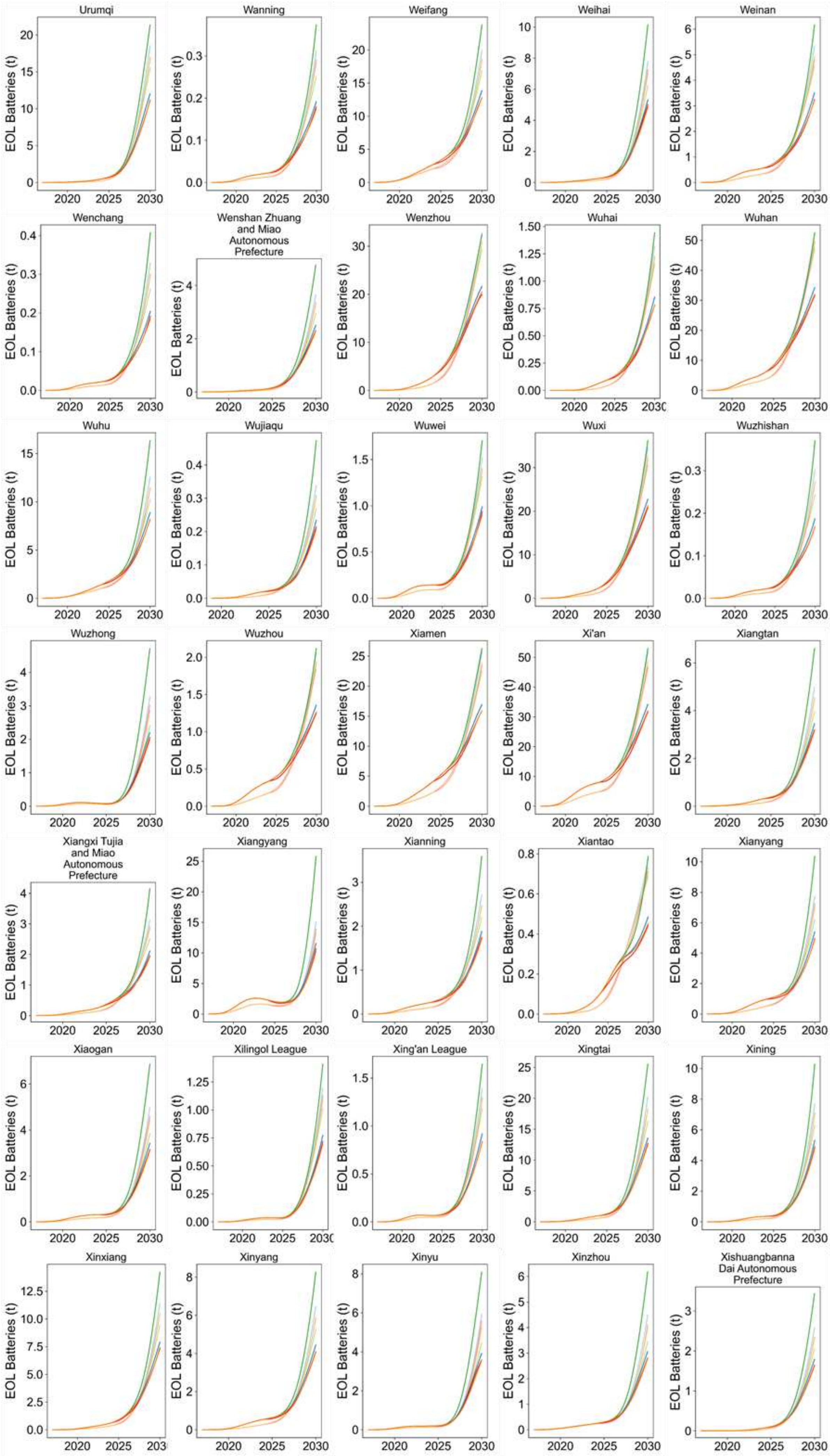
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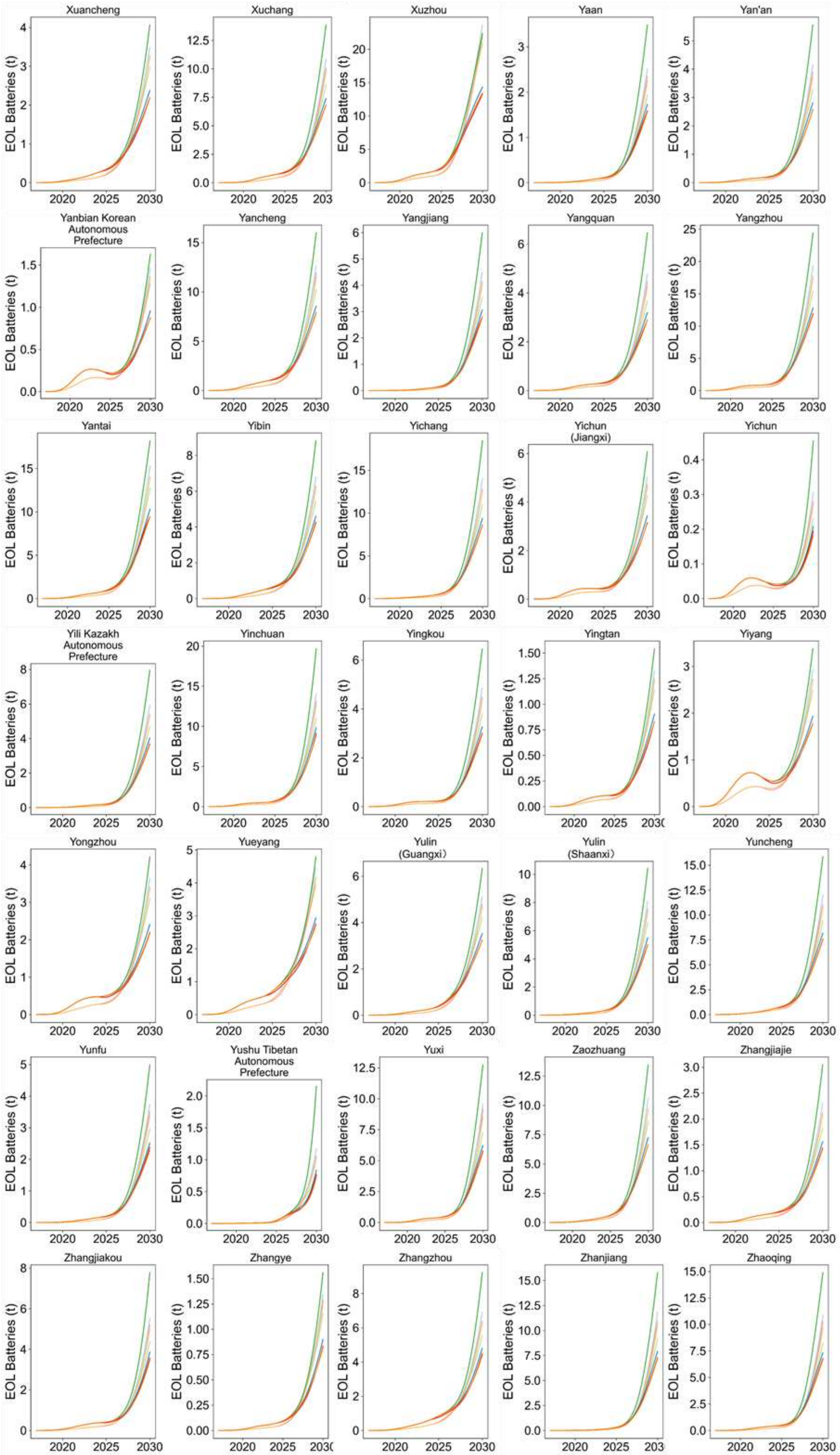
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Yichun
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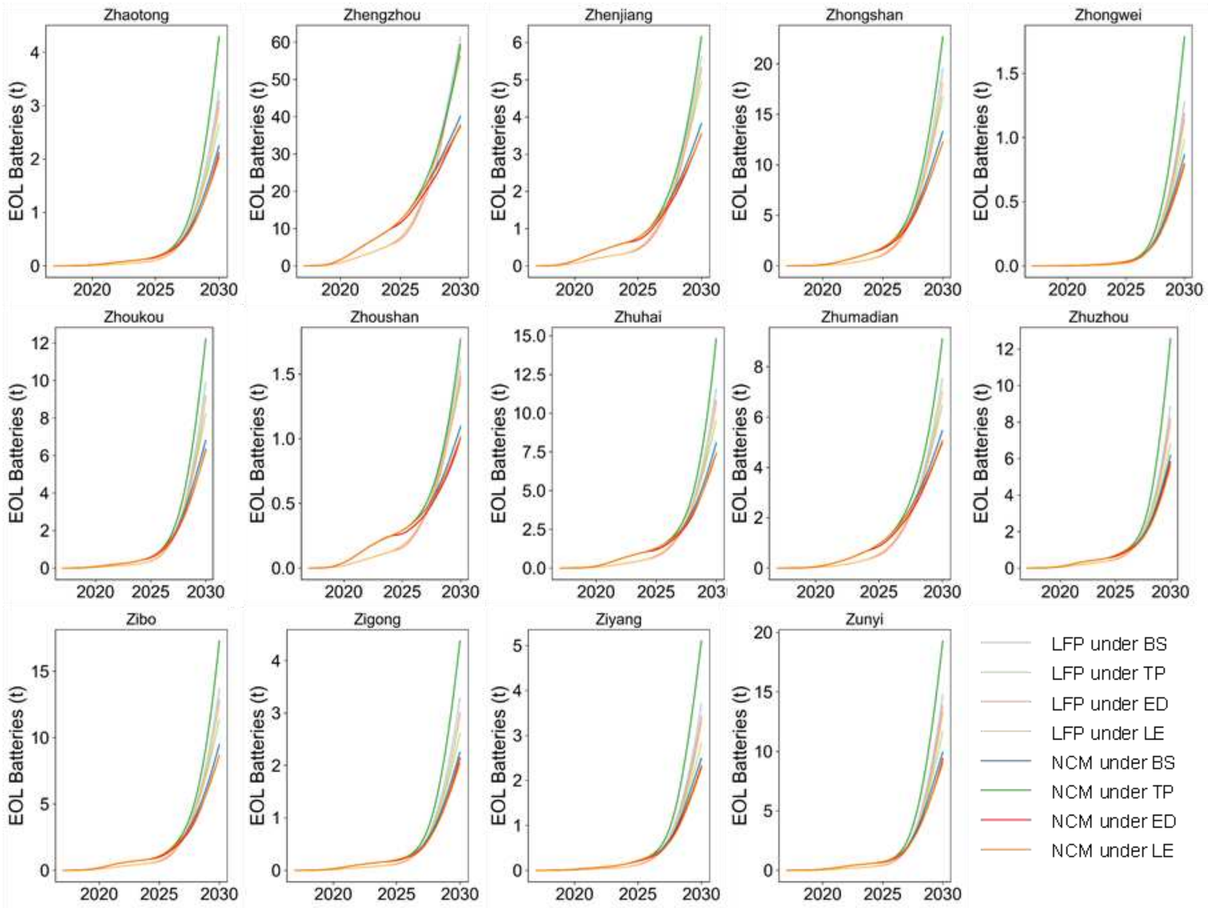

Figure S3. Volume EOL power batteries for LFP and NCM across 364 cities under various scenarios for the period 2020–2030

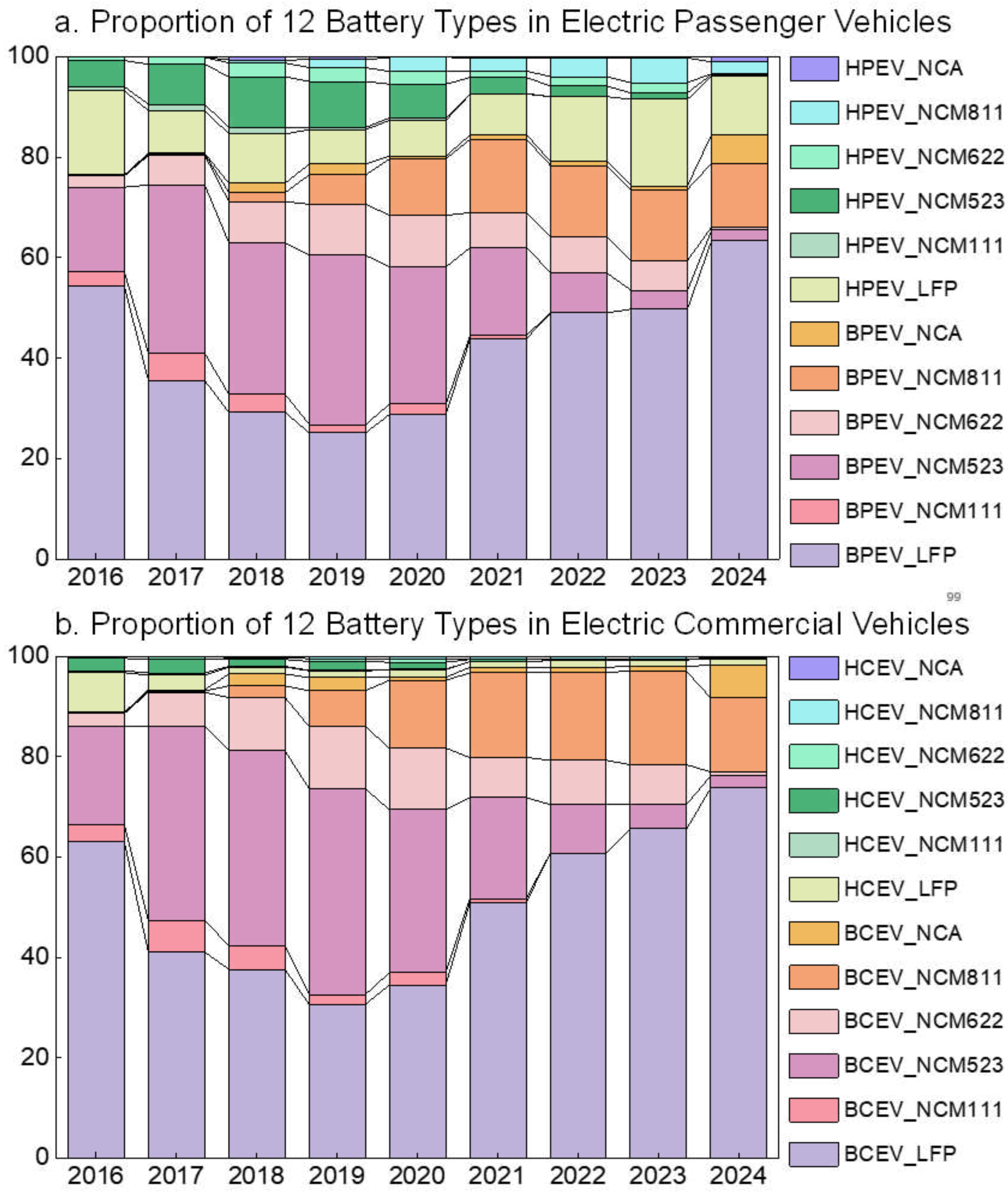

Figure S4. Market share of 24 battery types in electric vehicles during 2016–2024

a, Installed capacity of 12 battery types in electric passenger vehicles from 2016 to 2024. b, Installed capacity of 12 battery types in electric commercial vehicles from 2016 to 2024.

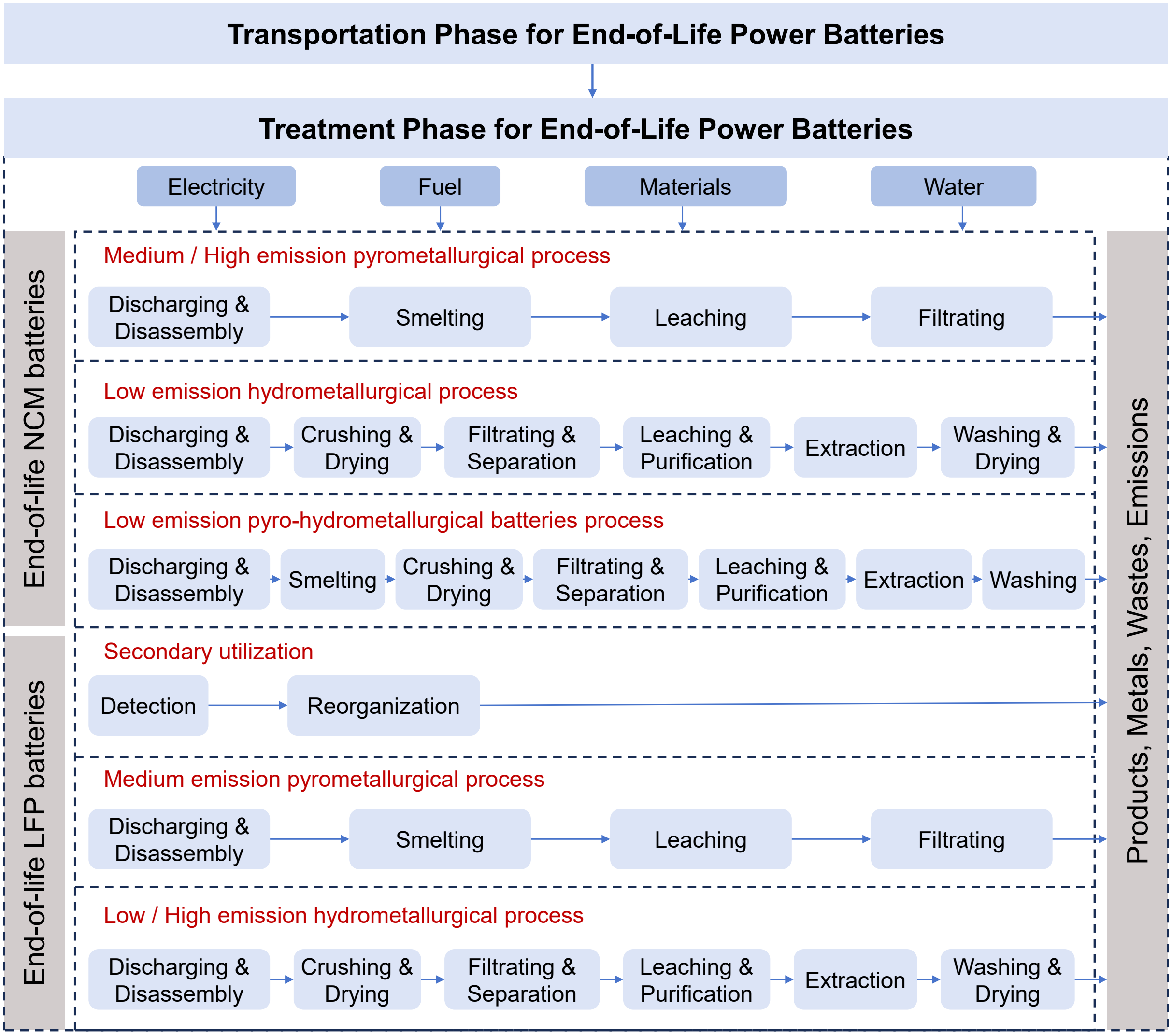

Figure S5. System boundary

* The system boundary encompasses battery transport; pre-processing and disassembly during the treatment stage; energy and material inputs; metal recovery; and end-of-life waste management.

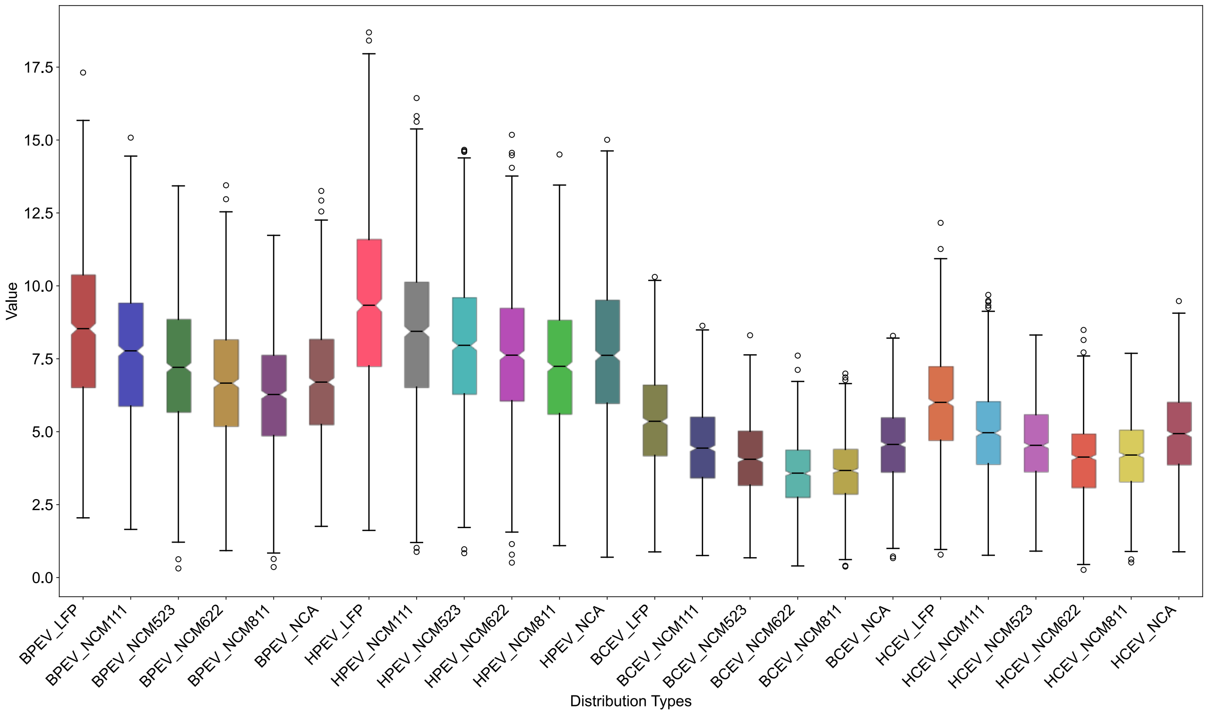

Figure S6. Weibull lifetime distribution parameters for 24 types of power batteries

Note: Box plots showing the statistical distribution of battery service lifetimes (in years) simulated using Weibull distributions for 24 distinct combinations of vehicle categories and battery chemistries. The analysis encompasses battery electric passenger vehicles (BPEV), hybrid electric passenger vehicles (HPEV), battery electric commercial vehicles (BCEV), and hybrid electric commercial vehicles (HCEV), each paired with six battery chemistry types: LFP, NCM111, NCM523, NCM622, NCM811, and NCA. Center line (horizontal bar within box): Median lifetime value (50th percentile). Box boundaries: Interquartile range (IQR), representing the 25th percentile (lower boundary) to 75th percentile (upper boundary) of the distribution. Whiskers: Extend to the minimum and maximum values within 1.5 × IQR from the lower and upper quartiles, respectively. Data points beyond this range would be plotted as individual dots (outliers), though none are visible in this visualization due to the continuous nature of the Weibull distribution sampling. Notch: Indicates the 95% confidence interval around the median; non-overlapping notches between groups suggest statistically significant differences in median lifetimes. Sample size: n = 1,000 independent Monte Carlo samples drawn from each Weibull distribution (total n = 24,000 samples across all 24 groups). Each sample represents a simulated battery lifetime trajectory based on the specified shape (k = 3.5 for all groups) and scale (λ, varying by battery type from 4.0 to 10.5 years) parameters.

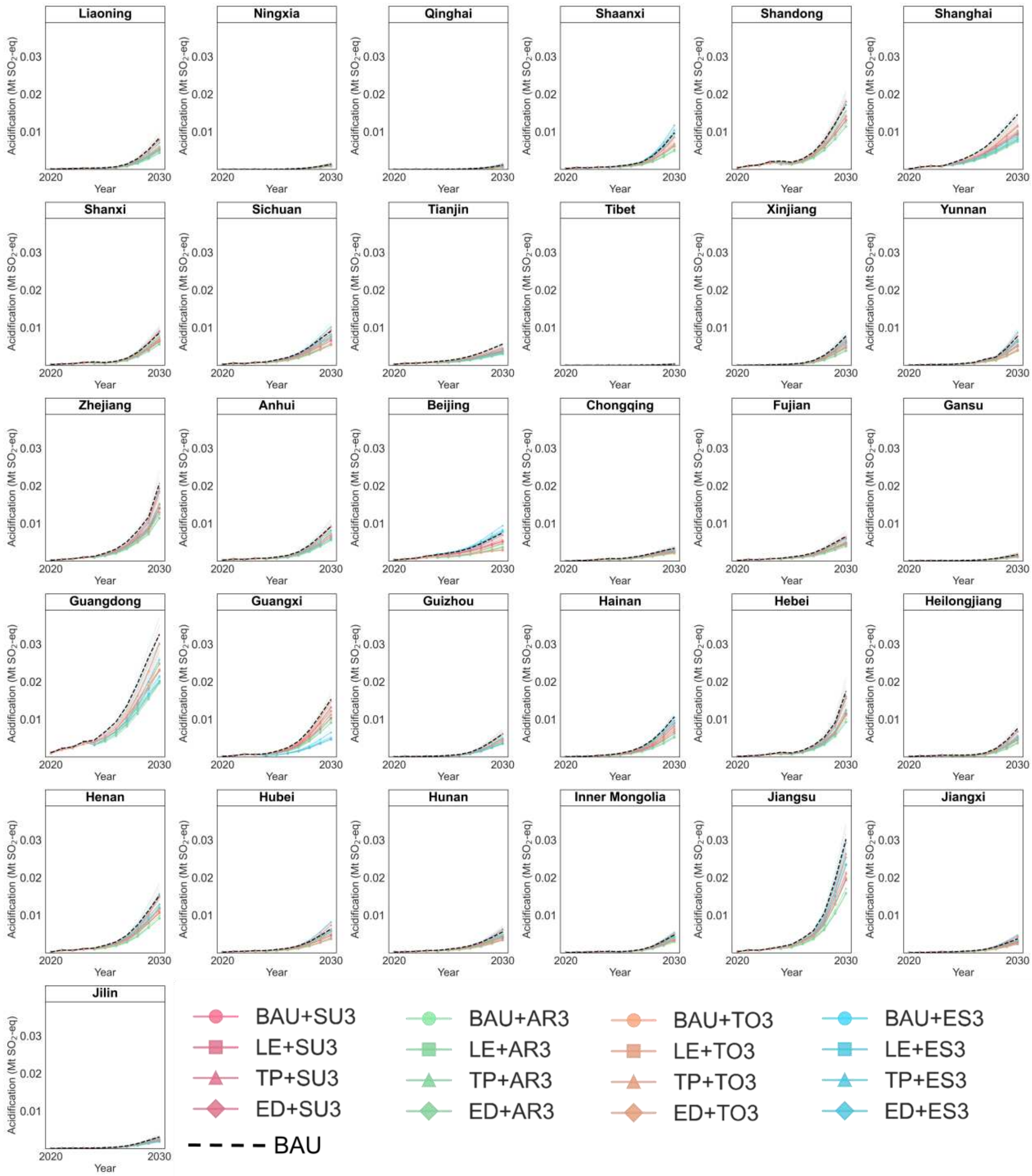

Figure S7. Acidification potential for each province from 2020 to 2030 under 52 scenarios

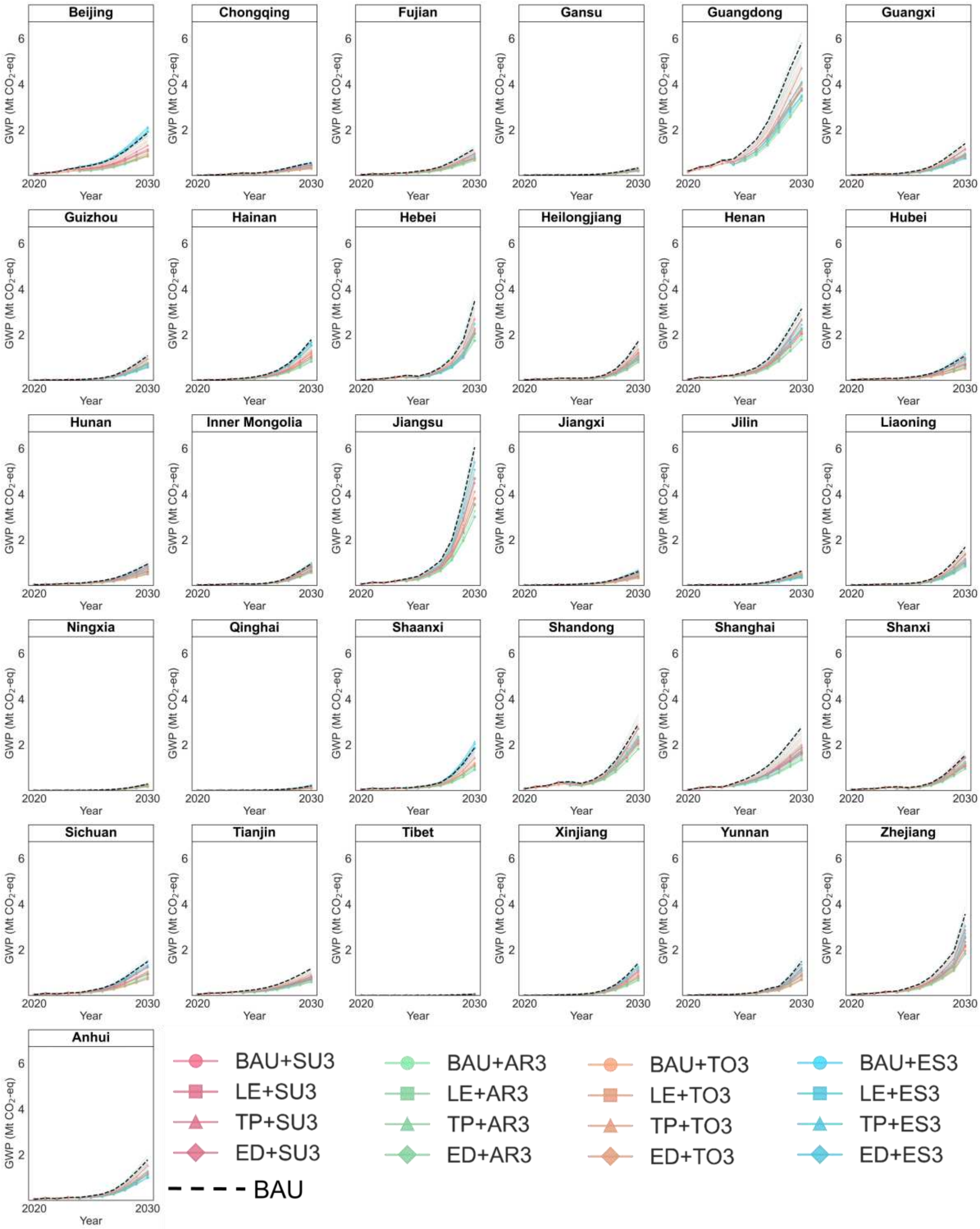

Figure S8. Global warming potential for each province from 2020 to 2030 under 52 scenarios

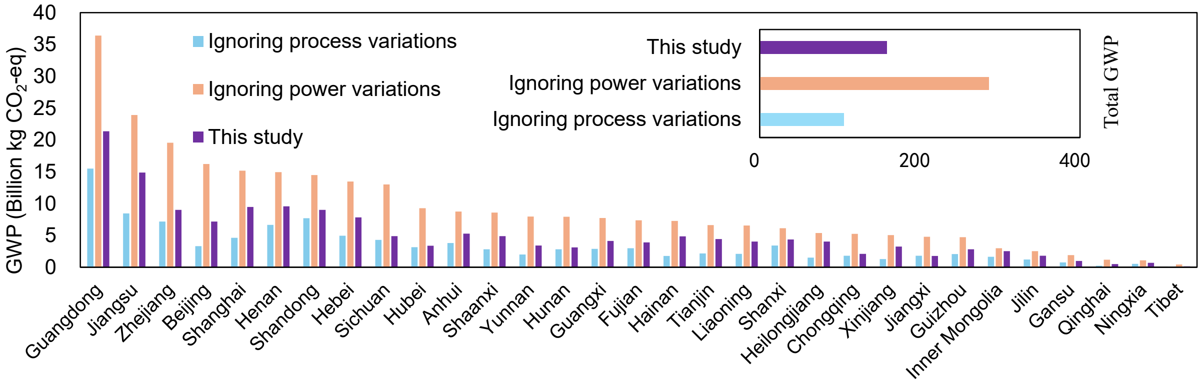

Figure S9. Comparison of GWP results between this study and scenarios ignoring provincial differences in electricity and technology.

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