

**Original Article**



# Macroeconomic Costs and Benefits of Energy Storage Configuration in China: Evidence from a Storage-Augmented Multi-Regional CGE Framework

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## Abstract:

Energy storage is usually evaluated as a power-system flexibility technology, but its economy-wide value also depends on investment demand, electricity-cost pass-through, renewable curtailment, sectoral output and interregional trade. This paper develops a transparent storage-augmented multi-regional computable general equilibrium (CGE) framework for China and applies it to a counterfactual experiment for 2024-2035. The framework explicitly separates public 2024 data anchors, calibrated regional-sectoral inputs, exogenous scenario assumptions and deterministic model outputs. The benchmark uses official GDP, macro-regional GDP, electricity consumption, renewable generation, renewable utilization and new-type energy-storage statistics. The 2035 values are not observed data or point forecasts; they are model-generated counterfactual outcomes under stated allocation rules, battery-cost assumptions and storage-coordination parameters. The model links a compact four-region, eight-sector SAM/MRIO benchmark with a storage-augmented electricity module in which storage affects effective variable renewable electricity through curtailment reduction, peak-cost smoothing and interregional balancing. Five scenarios are evaluated: business-as-usual growth, economically sized storage, resource-targeted storage, coordinated allocation and accelerated high deployment. In the central experiment, coordinated allocation reaches 320 GW and 1280 GWh of new-type energy storage by 2035, lowers the electricity-cost index to 97.4 relative to BAU, reduces the wind-solar curtailment proxy to 4.6%, and raises equivalent variation by 0.47%. The accelerated high-deployment scenario installs more capacity but produces a smaller welfare gain. Additional decomposition and robustness checks show that this ranking is driven by the interaction of allocation quality, coordination and investment crowding rather than by an assumed capacity target alone. The paper contributes a reproducible data pipeline, an explicit storage-CGE accounting structure and regional allocation rules that can be extended with a full provincial SAM and hourly dispatch module.

**Keywords:** social accounting matrix; renewable curtailment; electricity flexibility; multi-regional CGE; regional allocation; macroeconomic welfare; China; energy storage.

## Introduction

The rapid expansion of wind and solar power has changed the economic role of energy storage. Storage is no longer only an engineering device for short-term balancing. At high variable renewable energy (VRE) shares, storage affects the utilization rate of renewable generation, the

electricity price paid by firms and households, the location of investment, the demand for electrical equipment, and the distribution of gains between renewable-resource regions and load-center regions. These channels are macroeconomic because electricity is an intermediate input in

almost every sector and because storage investment competes with other forms of capital formation. A storage project that reduces curtailment in a resource region may lower generation cost and raise the effective supply of lowcarbon electricity. The same amount of storage installed without coordination may crowd out other investment and deliver a weaker welfare gain. Therefore, the central economic question is not only how much storage should be installed, but also how storage should be configured across regions and connected to power-system operation.

China provides a relevant setting for this question [1]. Official statistics report 2024 nominal GDP of 134,908.4 billion yuan and provide macro-regional GDP for the eastern, central, western and northeastern regions. National Energy Administration reports 2024 electricity consumption of 9852.1 TWh (equivalent to 98,521 108 kWh). Renewable energy also reached a scale at which flexibility constraints matter: by the end of 2024, renewable power capacity reached 1.889 billion kW, wind capacity reached 521 GW, solar PV capacity reached 886 GW, and wind plus solar generation was about 1.83 trillion kWh [2]. New-type energy storage, excluding conventional pumped storage, reached 73.76 GW with an average duration of 2.3 h by the end of 2024. These public values are used as calibration anchors. They are not replaced by simulation values, and the 2035 scenario results reported later are explicitly treated as model-generated counterfactual rather than measured statistics.

Power-system models can represent in detail, e.g. hourly dispatch, storage charging and transmission constraints. Usually, they treat final demand, sectoral production and household welfare as exogenous. Power-system models represent economy-wide market clearing and welfare effects by computable general equilibrium (CGE) models. Many top-down CGE models treat electricity as a homogeneous

commodity and therefore understate curtailment and flexibility constraints. It has been stressed in recent studies, that curtailment, storage and VRE integration costs should be represented in general equilibrium or integrated assessment frameworks [3]. Multi-regional CGE analysis shows that integration costs and regional spillovers can change the macroeconomic effects of renewable expansion [4]. In this paper, we combine these two of these with the insight that one can embed a reduced-form storage and curtailment channel in a compact MR-CGE benchmark.

This paper asks whether the macroeconomic benefit of storage in China comes mainly from the total amount of storage or from the configuration of storage across regions. The answer matters for policy design. If the benefits are mainly scale-driven, then capacity targets may be enough. If the benefits depend on where the storage is built and how it interacts with the renewable resources, demand centers and interregional balancing, storage policy should be looked at as a regional allocation problem. This paper contributes in three ways. First, it separates the public data anchors from the calibrated inputs, scenario assumptions and counterfactual outputs, so that the reviewers can identify which numbers are observed and which are produced by the model. Second, it documents a screening level CGE accounting implementation in the main manuscript, of the sectoral aggregation, of the benchmark SAM/MRIO coefficients, of the balance checks, of the elasticities, of the storage specific parameters and of the validation boundaries. Third, it compares storage quantity and storage configuration scenarios and add some isolation checks that separate the effects of capacity, allocation and coordination. The results show that the coordinated regional allocation can outperform a higher capacity but less coordinated deployment path and also clarifies the assumptions under which that ranking is obtained.

Figure 1 summarizes the modeling pipeline. The

image is used as a conceptual research-framework figure. It is not used as empirical evidence, and no numerical result is extracted from it. The caption makes it clear that this is an editorial schematic in order to avoid making the visual appear as an

observed dataset. The numerical figures and tables that follow are generated from the stated public anchors, calibrated parameters and deterministic scenario rules.



**Figure 1. Storage-augmented CGE accounting and scenario-simulation framework. The schematic distinguishes public data anchors, calibrated benchmark accounts, the storage-electricity bridge, the CGE accounting core and model-generated outcomes; it is not an empirical data source.**

## Literature Review and Contribution

### Storage, VRE Integration and Curtailment

The economic value of storage is closely related to the declining marginal value of VRE at high penetration. Hirth shows that the wind and solar market values fall as their shares rise because generation is correlated in time and can depress prices when in high-output periods. Ueckerdt et al. [5] formalize this issue as a system-cost problem and argue that the integration costs should be taken into account when variable renewables are compared with dispatchable technologies. Also, in the global integration review of the IEA it is stated that higher stages of VRE integration needs flexibility, grid reinforcement, improved market design and

storage and not simply capacity expansion. These studies show why a storage-capacity target cannot be assessed only through engineering cost: the same physical capacity can have different economic value under different curtailment, transmission and demand conditions.

Storage reduces curtailment by shifting surplus renewable electricity to hours or regions with higher value. But storage involves capital costs, efficiency losses, degradation and opportunity costs. For example, NREL [6] 2025 projection reports wide uncertainty in utility-scale lithium-ion battery costs; for a 4-hour system, 2035 low, mid and high projections are 147, 243 and 339 USD/kWh in 2024 dollars, and the assumed round-trip efficiency is 85%. This uncertainty

justifies a welfare based approach. A storage project is economically beneficial only if the avoided curtailment, avoided peaking costs, reliability value and spillover benefits is more than annualized investment and crowding costs .

### **CGE Models with Electricity and Storage Detail**

The standard CGE structure is calibrated to a social accounting matrix and solved under alternative policy closures. CGE models are useful for energy-policy analysis because they describe production, consumption, trade, investment and welfare in one market-clearing framework [7]. Energy-policy CGE applications commonly use nested CES technologies and Armington trade assumptions to represent substitution among capital, labor, energy, materials and regionally differentiated commodities [8]. The advantage of is that it can trace how a power-sector shock changes intermediate-input costs, household real income, regional trade flows and welfare at the same time.

Many CGE electricity blocks have the limitation that electricity is often represented as single commodity or as simple mix of technologies. Such structure does not capture the value of flexibility when renewable output is variable and location specific. Dai et al. include in a general equilibrium model the curtailment and the storage of VRE and show that these mechanisms affect the mitigation costs. Cui et al. show that the change of the electricity nesting structures alters the estimated impacts of the reducing renewable curtailment in China. Shi et al. analyse the renewable energy storage and the clean electrification in a CGE framework oriented to the China. In the present paper, we build on the studies of the above cited, we treat the storage as a balancing service that changes the effective VRE utilization, not as a generic electricity-generation technology.

### **Multi-Regional IO/CGE Evidence for China**

Storage configuration is spatial. Renewable resources are concentrated in some regions, while electricity demand, industrial output and service-sector income are concentrated in others. Multi-regional input-output datasets provide the accounting base for analysing these spillovers. Chinese provincial MRIO datasets covering 31 provinces and 42 sectors for 2012, 2015 and 2017 are available in the literature and from CEADs-related sources [9]. Earlier MRIO work maps China's regional outputs and interdependencies and is widely used for emissions and supply-chain analysis [10]. They show that regional electricity shocks can propagate through industrial supply chains rather than remaining local.

It is to be noted that the present manuscript does not claim to estimate a new official provincial MRIO table. The present manuscript builds a compact four-region, eight-sector benchmark that is consistent with public macroeconomic and electricity anchors. The choice has two purposes. First, it keeps the full pipeline transparent and reproducible in the present manuscript. Second, it makes clear what should be replaced in a later full-scale empirical implementation: the compact benchmark can be replaced by a provincial SAM, a full MRIO table, interprovincial electricity trade data and hourly dispatch results without changing the theoretical accounting structure.

### **Research Gap and Contribution**

It is well established in the literature that VRE integration costs matter and that CGE models can evaluate economy wide effects. Less attention has been given to the regional configuration of storage as a macroeconomic policy variable. Much of the existing work is there in the form of compare storage versus no storage, or maybe renewable expansion with and without curtailment but does not always, ask whether the same national storage capacity produces different macroeconomic outcomes when it is allocated to resource regions, load centers or coordinated regional hubs. In this paper we fill that gap, by

linking storage quantity, duration, allocation weights and coordination to CGE-accounting outcomes. We deliberately put the approach in the position of a transparent scenario-screening framework rather than as a claim to estimate a new official provincial SAM or an hourly dispatch equilibrium.

The contribution is the combination of a storage-

specific flexibility channel, a regional allocation rule and economy-wide welfare accounting in a single reproducible scenario framework. Table 1 summarizes how the present framework differs from the closest strands of the literature. The table is not meant to rank prior studies, it only clarifies how methodologically the niche of the paper is.

**Table 1. Positioning of the present study relative to selected literature.**

Study strand or example	Main contribution in the literature	Remaining gap addressed in this paper
VRE value and integration-cost studies	Explain why the market value of wind and solar declines at high penetration and why flexibility, curtailment and system costs matter.	Add regional CGE welfare, sectoral output and trade-spillover channels.
General-equilibrium storage or curtailment studies	Introduce storage, curtailment or electrification into economy-wide modeling.	Separate storage scale from spatial configuration and coordination quality.
Electricity-nesting CGE studies for China	Show that electricity nesting assumptions affect the estimated economic impacts of curtailment reduction in China.	Treat storage as a balancing service with explicit regional allocation weights.
Energy-system–CGE coupling studies	Link power-system integration costs or energy-system outputs to macroeconomic feedbacks.	Provide a transparent compact implementation and data-classification protocol for China.
This paper	Combines storage-specific curtailment reduction, peak-cost smoothing, interregional balancing and investment crowding in a four-region, eight-sector CGE accounting and scenario-simulation framework.	Tests whether coordinated allocation can outperform a higher but less coordinated deployment path and reports decomposition checks for capacity, allocation and coordination effects.

The analysis is deliberately transparent. All the public data, the calibrated inputs, and the model outputs are classified separately; all the values of 2035 are described as counterfactual outputs. It also separates the empirical inputs from the calibrated assumptions and the results of the deterministic scenario we run. This reduces the risk that the values we simulate are thought of as values we observed, and it makes the paper easier to extend when the compact calibration is

replaced by a fully replicable CGE implementation.

## Data, Benchmark Construction and Scenarios

### Public Calibration Anchors

The benchmark year is 2024. Table 2 lists the public data anchors used for calibration. These values enter the model as empirical inputs, and are not produced by the simulation. The main macroeconomic anchor is official GDP and

official macro-regional GDP from the National Bureau of Statistics [11]. The electricity demand by user group comes from the National Energy Administration's 2024 electricity-consumption release. The renewable generation, renewable capacity, wind utilization and solar utilization come from the NEA renewable grid-operation release [12]. The new-type energy-storage capacity and average duration come from the English-language State Council release citing NEA information. These values define the observed scale of the Chinese economy, power demand, renewable supply and storage deployment before any counterfactual scenario is introduced.

The calibration principle is conservative. We use

only values directly reported by the public sources in order to anchor the benchmark scale. Values not directly observed at the required regional-sectoral resolution are taken as calibrated input. For example, public sources provide us with the national electricity consumption and the macro-regional GDP, but they do not provide a complete 2024 four region, eight sector SAM with storage-service accounts. The missing accounts are therefore constructed, through the transparent shares and the consistency checks. It is important for the submission, because the 2035 storage capacity, curtailment proxy and welfare deviations of the model are not presented as actual forecast; they are deterministic output of the counterfactual design.

**Table 2. Public data anchors used for 2024 benchmark calibration.**

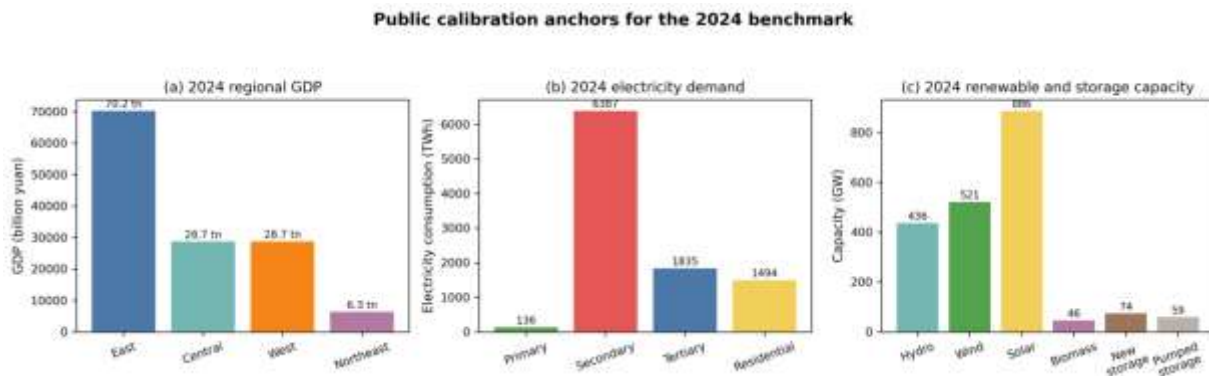
Category	Indicator	2024 value	Source class
Macroeconomy	Nominal GDP	134,908.4 billion yuan	NBS Statistical Communiqu 'e 2024
Regional GDP	Eastern region GDP	70,235.6 billion yuan	NBS Statistical Communiqu 'e 2024
Regional GDP	Central region GDP	28,715.6 billion yuan	NBS Statistical Communiqu 'e 2024
Regional GDP	Western region GDP	28,735.0 billion yuan	NBS Statistical Communiqu 'e 2024
Regional GDP	Northeastern region GDP	6,345.1 billion yuan	NBS Statistical Communiqu 'e 2024
Electricity	Total electricity consumption	9,852.1 TWh	NEA electricity consumption release
Renewables	Wind and solar generation	1,830.0 TWh	NEA renewable grid-operation release
Renewables	Wind utilization rate	95.9%	NEA renewable grid-operation release
Renewables	Solar PV utilization rate	96.8%	NEA renewable grid-operation release
Storage	New-type energy-storage power capacity	73.76 GW	English-language State Council release citing NEA
Storage	Average new-type energy-storage duration	2.3 h	English-language State Council release citing NEA
Storage	Pumped-storage hydropower capacity	58.69 GW	NEA renewable grid-operation release

Figure 2 visualizes the main public anchors. The

purpose is to show the empirical scale of the 2024

benchmark before introducing model-generated counterfactual values. The figure is not used to prove the model results; rather, it provides a

concise check that the subsequent scenario magnitudes are linked to plausible observed macroeconomic and energy-system quantities.



**Figure 2. Public calibration anchors for the 2024 benchmark. The plotted values are public statistical anchors, not model outputs.**

**Calibration Traceability and Balance Rules**

Each non observed variable is associated with an explicit calibration rule and a consistency check, in order to make the compact benchmark auditable. The procedure is designed to be conservative: the scale of the benchmark is the one given by the observed public totals, and the un observed regional-sectoral accounts are

constructed only as calibrated inputs. Table 3 reports the main traceability rules. It is worth to underline that in the paper we do not pretend that the compact four region SAM is an official statistical table. It is a balanced modeling benchmark that we use to translate the storage scenarios in the counterfactual macroeconomic ones.

**Table 3. Traceability rules used to convert public anchors into compact benchmark inputs.**

Model quantity	Anchor or basis	Calibration operation	Consistency check
Regional GDP weights	NBS macro-regional GDP	Normalize East, Central, West and Northeast GDP to national GDP-covered regions.	Regional shares sum to one after normalization.
Sectoral value-added shares	NBS primary/secondary/tertiary structure and CGE sector aggregation	Split secondary and tertiary activities into eight policy-relevant sectors using electricity-intensity and storage-investment relevance.	Sector shares sum to 100% and preserve the aggregate production structure.
Sectoral electricity use	NEA total electricity consumption and sector-use logic	Allocate 9852.1 TWh across the eight sectors according to electricity intensity and household/service residual demand.	Sectoral electricity totals sum exactly to the public national electricity-consumption anchor.

Model quantity	Anchor or basis	Calibration operation	Consistency check
Regional storage indices	VRE resource logic, load-center logic and trade-connectivity assumptions	Assign $q_r$ , $l_r$ and $m_r$ as transparent normalized indices rather than observed statistics.	Each index is bounded between 0 and 1 and is reported directly in Table 6.
IO/SAM coefficients	Compact SAM construction and standard CGE accounting	Assign normalized intermediate-input and value-added coefficients by sector.	For each column, intermediate-input share plus value-added share equals one.
Scenario outputs	Equations (17)–(18), the curtailment function and welfare calculation	Generate 2035 outcomes deterministically from scenario endpoints and calibrated parameters.	Outputs are classified as counterfactual model results, not observed statistics.

### Regional and Sectoral Aggregation

Let  $r \in R$  denote region and  $s \in S$  denote sector. The public GDP weight of region  $r$  is The regional aggregation uses four macro-regions: East, Central, West and Northeast. The East is treated as the main demand and manufacturing center, the West as the main renewable-resource region, the Central region as an intermediate demand-balancing region, and the Northeast as a smaller region with industrial and heating-load characteristics. The aggregation follows the NBS regional GDP classification and is sufficient to distinguish load-center and renewable-resource channels at the level of this paper.

$$\omega_{r,2024}^{GDP} = \frac{GDP_{r,2024}}{\sum_{r \in R} GDP_{r,2024}} \quad (1)$$

The model uses eight sectors: agriculture, mining

and fuels, energy-intensive manufacturing, other manufacturing, electricity and utilities, construction, transport and services. This aggregation is chosen to preserve the channels most relevant for storage policy. Energy-intensive manufacturing and electricity are separated because the change of electricity-cost and reduction of curtailment affect it directly. Construction and other manufacturing are separated because the storage investment raise the demand on equipment, engineering services and installation. Services are combined with the household direct electricity demand in the compact accounting structure because the paper is not interested by a detailed household microsimulation but by the regional welfare and the pass through of electricity-cost.

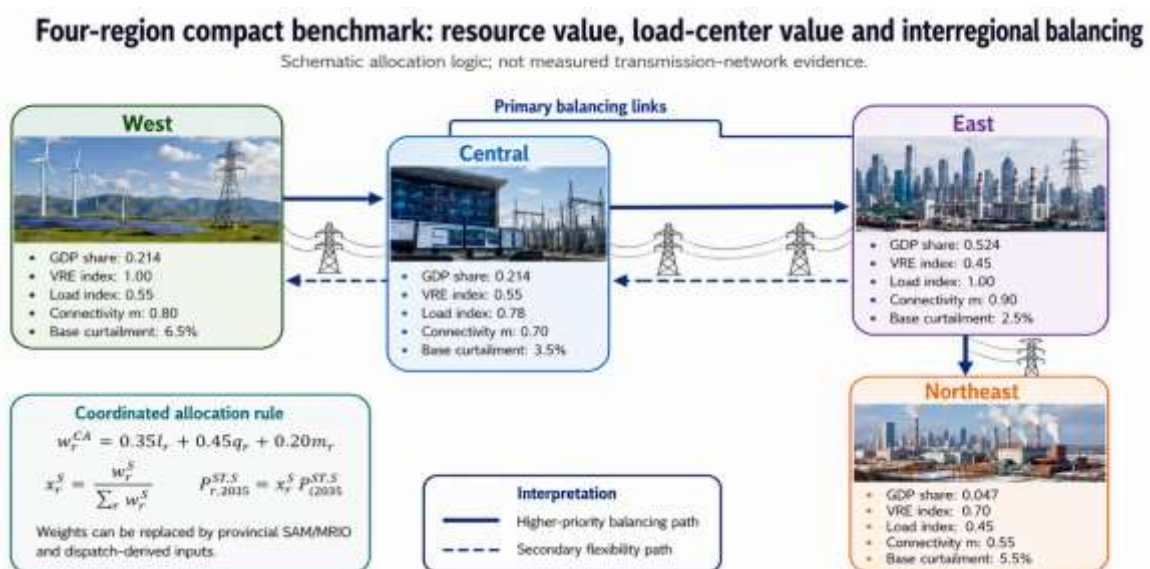
**Table 4. Sectoral aggregation and benchmark calibration shares.**

Code	Sector	NBS aggregate	Calibration note	VA share (%)	Electricity (TWh)
AGR	Agriculture	Primary industry	Public top-level share; sector equals primary industry.	6.8	135.7
MIN	Mining and fuels	Secondary industry	Calibrated split of secondary industry with high energy intensity.	4.0	580.0

Code	Sector	NBS aggregate	Calibration note	VA share (%)	Electricity (TWh)
EII	Energy-intensive manufacturing	Secondary industry	Calibrated split covering metals, chemicals, cement and related materials.	10.0	2050.0
OMF	Other manufacturing	Secondary industry	Calibrated manufacturing residual outside energy-intensive activities.	15.0	2400.0
PWR	Electricity and utilities	Secondary industry	Calibrated power, heat and utility account.	3.0	760.0
CON	Construction	Secondary industry	Construction account linked to storage investment demand.	4.5	597.4
TRN	Transport and storage	Tertiary industry	Transport and logistics account in tertiary production.	4.5	520.0
SER	Services plus household electricity demand	Tertiary industry and final demand	Residual tertiary services combined with household direct electricity demand.	52.2	2809.0

The visual is intentionally schematic. Figure 3 is placed in this section because it explains the regional logic of the scenario design. It is used to show the difference between resource regions, load centers and balancing links, not to report

actual transmission capacity at the line level. The numerical allocation used by the model is given in Table 6; the figure simply helps readers to understand the intuition behind the four-region configuration.



**Figure 3. Conceptual multi-regional energy-storage allocation scheme. The figure represents regional resource-load contrasts, allocation weights and interregional balancing links; lines and regional boxes are illustrative and are not a measured geographic or physical transmission-network dataset.**

### Benchmark SAM and MRIO Balancing

A full MR-CGE model needs a benchmark social accounting matrix that is consistent in commodity, activity, factor, institutional and trade accounts. The compact benchmark that we use in this paper is constructed in five steps. First: the regional value added is scaled to the public regional GDP anchors. Second: national sector value-added shares are allocated across regions using regional GDP shares and electricity-intensity modifiers. Third: normalized intermediate-input coefficients are assigned to the eight-sector IO block and checked so that each sector column shares sum to unity after value-added shares are included. Fourth: regional home-bias and interregional trade shares are assigned using GDP weight and a trade-connectivity index. Fifth: the electricity account is split into thermal electricity, dispatchable low-carbon electricity, effective VRE and storage service.

The SAM is not treated as an unreported dataset. It is a compact accounting device that makes the counterfactual experiment internally consistent. In

the present paper, the purpose is to show a reproducible storage-CGE method with explicit documentation of the calibration rather than to claim that the compact matrix is an official statistical product. In the main manuscript, the key checks are reported directly so that a reviewer can see whether the benchmark is balanced. In a full implementation, these coefficients should be replaced by a provincial SAM or MRIO table.

Let  $VA_{r,j}$  value added,  $X_{r,j}$  gross output, and let  $Z_{r,s,j}$  denote intermediate input from sector  $s$  to sector  $j$  in region  $r$ . The benchmark column balance is

$$\sum_{s \in S} Z_{r,s,j} + VA_{r,j} = X_{r,j}, \quad \forall r, j \quad (2)$$

The normalized coefficient version is

$$a_{s,j} = \frac{Z_{s,j}}{X_j}, \quad v_j = \frac{VA_j}{X_j}, \quad \sum_{s \in S} a_{s,j} + v_j = 1 \quad (3)$$

Table 5 reports the balance check for the compact benchmark. The values are normalized because the numerical experiment focuses on storage scenarios rather than estimating a new national IO table.

**Table 5. Normalized benchmark IO/SAM balance checks used by the compact MR-CGE calibration.**

Sector	Intermediate input share	Value-added share	Interpretation
AGR	0.280	0.720	Column shares sum to one before taxes and net imports.
MIN	0.420	0.580	Column shares sum to one before taxes and net imports.
EII	0.580	0.420	Column shares sum to one before taxes and net imports.
OMF	0.500	0.500	Column shares sum to one before taxes and net imports.
PWR	0.450	0.550	Column shares sum to one before taxes and net imports.
CON	0.550	0.450	Column shares sum to one before taxes and net imports.
TRN	0.380	0.620	Column shares sum to one before taxes and net imports.
SER	0.320	0.680	Column shares sum to one before taxes and net imports.

### Regional Storage Variables and Scenario Design

In the policy scenarios, three calibrated regional indices distribute storage in the . The VRE-potential index  $q_r$  captures the value of

renewable-resource . The load-center index  $l_r$  captures the value of peak-cost reduction near demand centers. The trade-connectivity index  $m_r$  captures the ability to exchange balancing services . They are not observed statistics but model inputs. We use them because storage delivers different services depending on the location. Storage in a high-resource region is mainly for reducing the curtailment and increasing the effective renewable output. Storage in a load center is mainly for reducing the peak-cost pressure and improving the electricity-price stability. Storage in a well-connected region can also provide balancing services to other regions

through the interregional coordination.

Table 6 reports the regional calibration inputs. The East receives the highest load-center and trade-connectivity scores because it has dense industry, services and electricity demand. The Central region is treated as an intermediate balancing region. The West receives the highest VRE-potential score and highest base curtailment proxy because it contains a large share of renewable-resource bases. The Northeast receives a smaller GDP share and lower connectivity score in the compact model, but its industrial and heating loads still make storage relevant in the scenario logic.

**Table 6. Regional calibration inputs for storage allocation weights.**

Region	GDP share	VRE potential	Load-center index	Trade connectivity	Base curtailment (%)
East	0.524	0.45	1.00	0.90	2.5
Central	0.214	0.55	0.78	0.70	3.5
West	0.214	1.00	0.55	0.80	6.5
Northeast	0.047	0.70	0.45	0.55	5.5

Table 7 reports the 2035 scenario endpoints used

by the deterministic model. Five scenarios are used. BAU assumes moderate growth in storage deployment and represents continuation of current deployment. ES gives greater weight to load centers and tests the value of economically sized storage located near demand. RT gives greater

weight to renewable-resource regions and tests the curtailment-reduction value of storage. CA uses a coordinated allocation rule over resource value, load-center value and connectivity. AHD installs more storage than CA but assumes weaker coordination and lower investment efficiency. This scenario is included to test whether simply installing more storage produces larger macroeconomic benefits.

**Table 7. Scenario design for storage configuration.**

Code	Scenario	Storage power (GW)	Duration (h)	Wind+solar share (%)	Coordination index
BAU	Business-as-usual storage growth	160	3.2	42.0	0.00
ES	Economically sized storage	240	3.6	44.0	0.25
RT	Resource-targeted storage allocation	280	3.8	46.0	0.45
CA	Coordinated multi-regional allocation	320	4.0	48.0	0.75
AHD	Accelerated high deployment	360	4.0	50.0	0.35

**Table 8. Rationale for scenario endpoints and allocation rules.**

Code	Scenario interpretation	Endpoint rationale	Main reviewer-facing interpretation
BAU	Continuation path after the rapid 2024 storage build-out	Extends the 2024 public storage anchor toward moderate 2035 growth without adding explicit interregional coordination.	Baseline counterfactual rather than a policy recommendation.
ES	Load-center-oriented economic sizing	Raises capacity above BAU and places more weight on $l_r$ so that storage is concentrated where peak-cost smoothing is most valuable.	Tests whether storage near demand centers is sufficient to generate macroeconomic gains.
RT	Renewable-resource-oriented allocation	Raises capacity and places more weight on $q_r$ so that storage is concentrated where curtailment pressure is higher.	Tests the curtailment-reduction channel separately from the load-center channel.
CA	Coordinated allocation over resource, load and connectivity values	Uses a four-hour storage duration and the allocation weight in Equation (17); the higher coordination index represents market, dispatch and transmission coordination rather than additional free capacity.	Central policy experiment for configuration-sensitive welfare effects.
AHD	Quantity-heavy high deployment with weaker coordination	Installs more national storage than CA, but assumes lower coordination and lower investment efficiency to represent capacity expansion that is not fully aligned with resource-load-balancing conditions.	Stress test of whether a larger physical target alone outperforms coordinated placement.

The endpoints in Table 7 should therefore be interpreted as scenario assumptions, not forecasts. They are bounded by (1) the observed 2024 storage scale, (2) policy emphasis on large-scale and market oriented new energy-storage development, and (3) the uncertainty in future battery-system costs [13]. The coordination index is also a scenario variable, rather than an observed institutional score. It is used to isolate whether storage with the same engineering function produces different macroeconomic effects when dispatch, interregional balancing and market participation are more or less coordinated. Table 8 makes this interpretation explicit so that the results are not read as mechanical forecast of China's 2035 storage capacity.

### Data Classification and Reproducibility

The manuscript separates four data classes. Public anchors are observed values that we have from a official or technical source. Calibrated inputs are transparent modeling choices that we used to construct the compact CGE accounting benchmark. Scenario assumptions are the exogenous storage, VRE-share and coordination pathways. Counterfactual outputs are the values generated by the equations in Section sec:model. Hence values such as 2035 GDP deviation, equivalent variation, storage allocation and curtailment proxy should be cited as model outputs, not as measured statistic. This is the language we used in the Results section in order to reduce the risk that the reviewers interpret the scenario results as unobserved empirical data.

**Table 9. Data classes and how they are used in the manuscript.**

Data class	Examples	Role in the model	Submission interpretation
Public anchors	2024 GDP, regional GDP, electricity consumption, wind-solar generation, utilization rates and storage capacity	Fix the observed benchmark scale and provide plausibility checks.	Empirical inputs from cited public sources.
Calibrated benchmark inputs	Sector shares, IO coefficients, regional indices, elasticities and storage parameters	Complete missing regional-sectoral accounts and define behavioral responses.	Transparent modeling choices, not official statistics.
Scenario assumptions	2035 storage capacity, storage duration, wind-solar share and coordination index	Define counterfactual policy paths for BAU, ES, RT, CA and AHD.	Exogenous scenario design.
Model outputs	GDP deviation, EV, cost index, curtailment proxy, sectoral effects and allocation outcomes	Report deterministic consequences of the equations and parameters.	Counterfactual results; not historical data or forecasts.

Figures 1 and 3 are editorial schematic diagrams. They contain no empirical geospatial information and no numerical results. Figures 2-6 are numerical visualizations based on public anchors, calibrated inputs and deterministic scenario rules. The tables are placed in the main manuscript in order to keep the submitted version self-contained. The supplementary data files are used as replication materials rather than as files required to interpret the results.

## Model

### Multi-Regional CGE Equilibrium Structure

The model is a recursive-dynamic storage-augmented CGE accounting framework with regions, sectors, representative households, government, investment and interregional trade. The storage policy path is exogenous in the central experiment so that the comparison is for the purpose of isolating the effect of storage quantity and configuration. In each period, producers minimize costs, households maximize utility subject to income, commodity markets clear, factor markets clear under the chosen

closure, and regional trade flows satisfy Armington aggregation. The solution concept is a sequence of static equilibria connected by capital accumulation, storage deployment and technology-cost trajectories. The recursive structure is sufficient for the purpose of the paper, because the main question of the paper is a comparative scenario evaluation, and not perfect-foresight optimization.

In the model, additional storage requires investment resources and therefore generates both a benefit channel and a crowding channel. The model closure follows the standard applied CGE convention for medium-run energy-policy analysis. Labor supply is fixed at the benchmark growth path and mobile across sectors within a region. Capital is sector specific within a period but accumulates recursively through investment. Government demand is fixed in real terms relative to the baseline path, while household consumption adjusts through income and prices. The national external balance is kept on the baseline path so that welfare differences are driven by domestic production, investment and

electricity-system effects rather than by arbitrary changes in foreign savings. These closure choices are conventional, but they are stated explicitly because storage investment can be otherwise mistaken for a free stimulus.

A compact zero-profit condition for activity (r,s) is

$$P_{r,s,t}^Y = c_{r,s,t}(P_{r,t}^K, P_{r,t}^L, P_{r,t}^E, P_{r,s,t}^M; A_{r,s,t}) \quad (4)$$

where  $P^Y$  is the output price and  $c()$  is the unit cost function implied by the nested production technology. Commodity-market clearing is

$$Q_{r,s,t} = C_{r,s,t} + I_{r,s,t} + G_{r,s,t} + \sum_{j \in S} a_{r,j,s,t} Y_{r,j,t} + EX_{r,s,t} - IM_{r,s,t} \quad (5)$$

The model is Walrasian: equilibrium prices clear commodity and factor markets, and one price is chosen as numeraire. The compact implementation is not presented as a black-box model, but rather as a transparent scenario solver. Regional and sectoral accounts are balanced first to the public 2024 anchors; storage scenarios update curtailment, effective VRE, electricity-cost pressure, investment demand and welfare by the

stated equations. This implementation is not meant as a substitute for a full GAMS/MPSGE implementation or for a provincial CGE solver. Its purpose is that in this auditable CGE accounting framework every numerical result can be traced to a public anchor, to a calibrated input, to a scenario assumption or to an explicit reduced-form response equation. Table 11 states this scope directly, because the paper is intended as a reproducible policy-screening implementation that can later be replaced by a full provincial SAM and dispatch-coupled CGE solver.

### Computational Implementation and Replication Workflow

The numerical implementation is the same as the deterministic workflow in Table 10. I included that table to make the computation auditable for the reviewers. It also explains why the 2035 values reported above should be understood as outputs of the scenario: the model does not try to estimate future observations; it applies a set of equations and allocation rules which are very transparent to the calibrated benchmark.

**Table 10. Scenario-solver workflow used to generate the numerical results.**

Step	Operation	Main inputs	Output or check
1	Load public anchors	GDP, regional GDP, total electricity, renewable generation, utilization and storage capacity	2024 benchmark scale.
2	Build compact regional-sector benchmark	Sector value-added shares, electricity-use allocation and IO/SAM coefficients	Balanced four-region, eight-sector account.
3	Define storage scenarios	Storage power, duration, wind-solar share and coordination index for BAU, ES, RT, CA and AHD	Scenario-specific storage-energy capacity.
4	Allocate storage by region	GDP weights, VRE-potential index, load-center index and trade-connectivity index	Regional storage allocation shares.
5	Update electricity channel	Curtailment function, storage service, battery efficiency and coordination parameter	Effective VRE, curtailment proxy and electricity-cost index.
6	Compute macroeconomic responses	Production elasticities, Armington assumptions, investment crowding and welfare equations	GDP deviation, EV, sectoral output and emissions deviation.
7	Validate and export	Balance checks, scenario endpoint	Tables, figures and

Step	Operation	Main inputs	Output or check
	results	table and sensitivity cases	supplementary replication files.

**Table 11. Methodological scope and validation boundary of the compact implementation.**

Reviewer concern	Current implementation	Validation or transparency check	Full-scale extension
CGE accounting consistency	Four-region, eight-sector benchmark with value-added, intermediate-input, electricity and trade accounts.	Public GDP and electricity totals are matched; IO/SAM column shares satisfy the balance conditions in Equations (2)–(3).	Replace compact coefficients with a provincial SAM and full MRIO table.
Storage-electricity mechanism	Annual reduced-form bridge from storage energy capacity to effective VRE, curtailment and electricity-cost pressure.	Parameters are reported in Table 12; outputs are stress-tested in Tables 14 and 15.	Estimate the curtailment response from hourly dispatch or unit-commitment simulations.
Policy endogeneity	Storage capacity, duration and coordination are exogenous scenario assumptions.	Table 8 distinguishes scenario design from observed data and forecasts.	Endogenize storage investment through profit conditions or power-market capacity values.
Regional spillovers	Interregional effects are represented by trade-connectivity weights and Armington-style commodity flows.	Regional indices are shown in Table 6; allocation rules are stated in Equations (17)–(18).	Use interprovincial electricity-flow data, transmission constraints and detailed regional trade matrices.
Welfare interpretation	Equivalent variation is measured relative to BAU and reported with GDP, cost and curtailment indicators.	Welfare results are not described as statistical estimates; they are deterministic counterfactual outputs.	Add household groups, income distribution and factor-market heterogeneity.

**Production, Trade and Household Blocks**

Sectoral production uses a nested CES representation. A compact top nest is

$$Y_{r,s,t} = A_{r,s,t} [\alpha_{r,s} K_{r,s,t}^{\rho_s} + \beta_{r,s} L_{r,s,t}^{\rho_s} + \gamma_{r,s} E_{r,s,t}^{\rho_s} + \delta_{r,s} M_{r,s,t}^{\rho_s}]^{1/\rho_s} \quad (6)$$

where K, L, E and M are capital, labor, energy and intermediate materials. The substitution elasticity is  $\rho_s$ , where  $\rho_s < 1$ . Energy-intensive manufacturing and electricity use lower substitution elasticities than services because their production technologies are more constrained in

the short and medium run. Services and other manufacturing use higher elasticities because firms have more scope to adjust production methods, intermediate input bundles and capital intensity.

Trade follows an Armington composite between

domestic and imported varieties:

$$Q_{r,s,t} = \left[ \eta_{r,s} D_{r,s,t}^{\theta_s} + (1 - \eta_{r,s}) IM_{r,s,t}^{\theta_s} \right]^{1/\theta_s}, \quad \sigma_s^A = \frac{1}{1-\theta_s} \quad (7)$$

At the interregional level, the same logic is used to distinguish local supply from supply originating in other regions. It matters because the benefit of storage is partly transmitted through regional electricity-cost differences. If storage lowers the electricity-cost index in a resource region, the direct effect appears in that region's

Representative household income is

$$YH_{r,t} = w_{r,t} L_{r,t} + r_{r,t} K_{r,t} + TR_{r,t} - TAX_{r,t} \quad (8)$$

and household utility is Cobb-Douglas in the compact version:

$$U_{r,t} = \prod_{s \in S} C_{r,s,t}^{\mu_{r,s}}, \quad \sum_{s \in S} \mu_{r,s} = 1 \quad (9)$$

This utility structure is transparent and stable for the counterfactual experiment. In a full empirical implementation, the household groups can be disaggregated by income, urban-rural status or region. The welfare measure we use here is equivalent variation as a percentage of benchmark consumption, which is easier to interpret than

electricity account. If the region trades energy-intensive goods or balancing services with other regions, the effect also propagates through interregional commodity flows. The compact model represents this through the trade-connectivity index and the calibrated trade shares.

nominal income because it keep price changes under control.

### Storage-Augmented Electricity Nest

The regional electricity composite is Because storage changes the effective supply and value of VRE, electricity is separated from the generic energy aggregate .

$$EL_{r,t} = \left[ \lambda_T (EL_{r,t}^T)^{\rho_E} + \lambda_D (EL_{r,t}^D)^{\rho_E} + \lambda_V (EL_{r,t}^V)^{\rho_E} + \lambda_S (ST_{r,t})^{\rho_E} \right]^{1/\rho_E} \quad (10)$$

where  $EL^T$  is thermal electricity,  $EL^D$  dispatchable low-carbon electricity,  $EL^V$  effective VRE and ST storage service. Thus, in this design, storage is not treated as free electricity generation. It is a service that increases the usable value of variable renewable output and reduces electricity-

system penalties. The design follows the intuition of the studies of VRE integration: storage should be designed to be valued for shifting, smoothing and firming power, and not only for adding installed capacity of the system.

Effective VRE is

$$EL_{r,t}^{V,\text{eff}} = EL_{r,t}^{V,\text{pot}} (1 - \kappa_{r,t}) \quad (11)$$

where  $\kappa_{r,t}$  is the curtailment rate. Storage service is proportional to usable energy capacity and utilization:

$$ST_{r,t} = \eta^{rt} H_{r,t} P_{r,t}^{ST} u_{r,t}^{ST} \quad (12)$$

where  $P^{ST}$  denotes power capacity,  $H$  denotes duration,  $u^{ST}$  denotes utilization,  $\alpha$  is a conversion parameter, and where we have denoted by  $\eta$ , the round-trip efficiency, and by  $\tau$ , the storage-service term. The storage-service term is deliberately written in energy-capacity form because the

$$\kappa_{r,t} = \max \left\{ 0, \kappa_r^0 + a_\kappa (v_{r,t} - v^0)^2 - b_\kappa \ln(1 + E_{r,t}^{ST}) - c_\Omega \Omega_t \right\} \quad (13)$$

where  $v_{r,t}$  is the wind-solar electricity share,  $E_{r,t}^{ST} = H_{r,t} P_{r,t}^{ST}$  and  $\alpha$  is the coordination index. The nonlinear term reflects the fact that curtailment and balancing pressure rise more than proportionally at high VRE shares. The logarithmic storage term reflects diminishing marginal curtailment reduction from storage capacity. The coordination term captures market dispatch, transmission coordination and

policy targets are often stated in GW, and because the power-system flexibility also depends on duration and usable on energy .

Curtailment is represented by a reduced-form function:

institutional arrangements that allow storage in one region to provide value beyond its local node. This equation is not a substitute for hourly dispatch; it is a transparent bridge between power-system mechanisms and the annual CGE accounting structure.

**Recursive Dynamics, Investment Cost and Welfare**

Capital evolves recursively:

$$K_{r,s,t+1} = (1 - \delta_s) K_{r,s,t} + I_{r,s,t} \quad (14)$$

Storage investment enters the investment-demand vector and creates both an industrial-demand channel and a crowding channel. Annual storage capital expenditure is

$$CAPEX_t^{ST} = \Delta E_t^{ST} C_t^{BESS} \quad (15)$$

where, and  $C_t^{BESS}$  is the battery system cost, and  $\Delta E_t^{ST}$  is the annual new storage energy capacity, i.e. , where in the central scenario, is the NREL mid cost path of . When the storage costs is decrease, the same storage-energy addition can absorb less investment resource. When the storage deployment is accelerated without coordination,

the additional capital stock can raise the output of equipment and construction, but if it does not sufficiently reduce the curtailment or the pressure of electricity-cost, it still can generate a lower welfare gain.

Equivalent variation is measured against BAU:

$$EV_{r,t} = \frac{e(P_{r,t}^0, U_{r,t}^S) - e(P_{r,t}^0, U_{r,t}^0)}{Y_{r,t}^0} \times 100 \quad (16)$$

where  $e()$  is the expenditure function, superscript 0 denotes BAU and superscript S denotes a storage scenario . The national EV indicator is the GDP-weighted regional aggregate . EV is the preferred welfare measure because GDP alone

can rise when investment rises even if households face higher prices or lower real consumption. Reporting both GDP and EV therefore helps to distinguish output expansion from welfare improvement.

**Calibration, Parameters and Validation**

The coordinated allocation weight is

$$w_r^{CA} = 0.35l_r + 0.45q_r + 0.20m_r \tag{17}$$

and storage allocation is

$$x_r^S = \frac{w_r^S}{\sum_{r \in R} w_r^S}, \quad P_{r,2035}^{ST,S} = x_r^S P_{2035}^{ST,S} \tag{18}$$

BAU allocation follows GDP shares. ES places greater weight on  $l_r$ , RT places greater weight on  $q_r$ , CA uses Equation (17), and AHD uses a quantity-heavy rule with lower investment efficiency. This structure allows the same national technology to produce different regional macroeconomic outcomes through different placement and coordination assumptions.

Table 12 reports the key elasticities and technical parameters. The elasticities follow common CGE ranges and the storage parameters follow NREL's 2025 battery-cost and performance assumptions

where available. The compact model is validated through three checks. First, the 2024 benchmark reproduces the public GDP and electricity anchors. Second, the IO coefficient columns satisfy Equation (3). Third, the 2035 endpoints in Table 13 are deterministic consequences of the scenario rules and parameter values stated in the manuscript. These checks do not prove that the model is the only possible representation of China's energy economy, but they do show that the reported results are internally consistent and reproducible.

**Table 12. Key elasticities and technical parameters.**

Parameter group	Symbol	Value/range	Source or basis	Model role
Production CES elasticity, non-electric sectors	$\sigma_{KLE}$	0.35–0.80 by sector	Sectoral calibration; GTAP/CGE literature range	Lower values for power and energy-intensive sectors.
Armington substitution elasticity	$\sigma_A$	1.5–3.0 by sector	Armington (1969); GTAP parameter documentation	Higher values for tradable manufacturing, lower for services.
CET export transformation elasticity	$\sigma_T$	1.5–2.5	Standard recursive CGE closure	Used only in robustness interpretation.
Electricity technology substitution elasticity	$\sigma_{EL}$	1.20	Dai et al. (2017); Pietzcker et al. (2017)	Represents imperfect substitution across thermal, dispatchable low-carbon and effective VRE.
Storage service	$\sigma_{ST}$	0.85	Storage-CGE calibration	Storage is a balancing

Parameter group	Symbol	Value/range	Source or basis	Model role	
substitution elasticity				service rather than a perfect generation technology.	
Battery round-trip efficiency	$\eta^{rt}$	0.85	NREL 2025 utility-scale battery assumptions	Applied to usable storage service.	
Battery lifetime	life <sup>ST</sup>	15 years	NREL 2025 utility-scale battery assumptions	Used for annualized cost interpretation.	
Fixed O	M cost	FOM <sup>ST</sup>	4% of power-capacity cost	NREL 2025 utility-scale battery assumptions	Sensitivity rather than central output driver.
Depreciation rate of reproducible capital	$\delta_K$	0.05–0.08	Recursive CGE convention	Sector-specific in full implementation; compact model uses representative interval.	
Curtailement curvature	$a_K$	0.65	Calibrated to match 2024 utilization and scenario endpoints	Determines nonlinear VRE penalty.	
Storage curtailement-reduction parameter	$b_K$	0.18	Calibrated electricity-system reduced form	Maps storage energy capacity to effective VRE absorption.	
Coordination parameter	$c_\Omega$	0.75	Policy scenario calibration	Captures market, transmission and dispatch coordination.	

## Results

### Cost and Deployment Paths

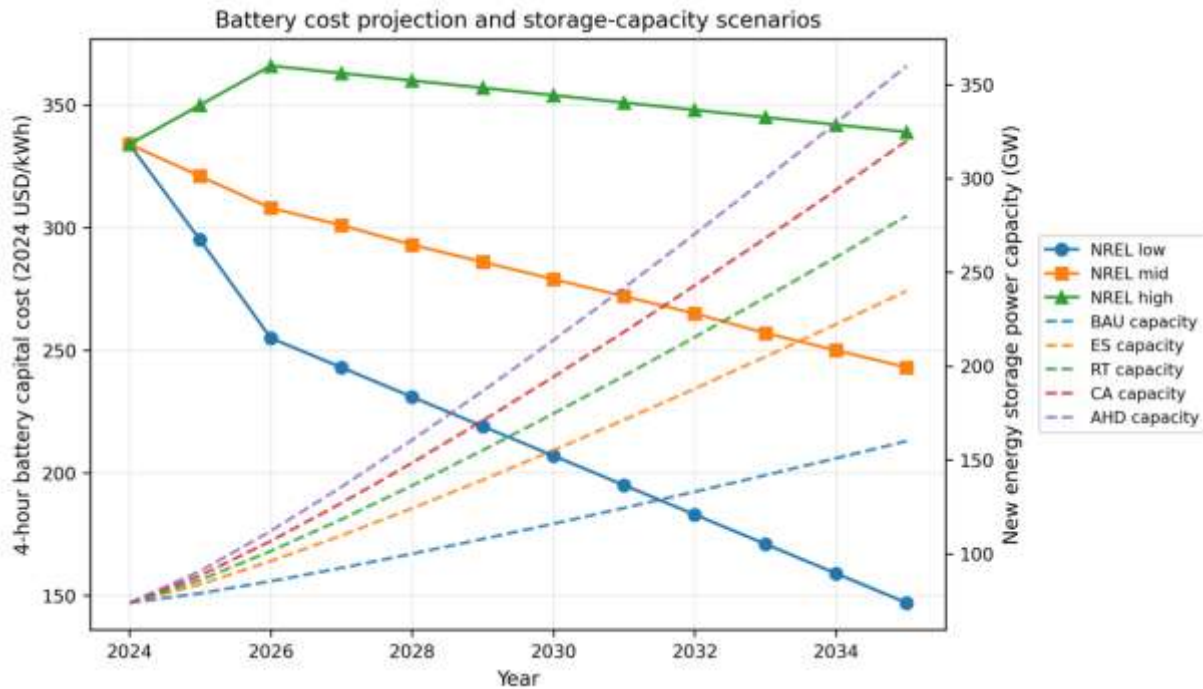
Figure 4 combines the NREL 4-hour battery-cost projection and the storage-capacity paths used in the five scenarios. The cost path is a public technical assumption. The storage-capacity paths are exogenous scenario inputs. The mid-cost path declines from 334 USD/kWh in 2024 to 243

USD/kWh in 2035. The low and high 2035 values are 147 and 339 USD/kWh, respectively [14]. These values define the investment-cost environment in which storage is expanded in . The scenarios do not assume that storage is free or automatically beneficial; each additional GWh creates both a flexibility benefit and a capital requirement. Figure 4. The NREL 4-hour battery-cost projection and the storage-capacity paths

used in the five scenarios.

The deployment paths are designed to separate scale from configuration. BAU grows from the observed 2024 storage anchor to 160 GW by 2035. ES reaches 240 GW and emphasizes load centers. RT reaches 280 GW and emphasizes renewable-resource regions. CA reaches 320 GW and uses the coordinated allocation rule that

combines load, resource and connectivity indices. AHD reaches 360 GW and therefore has the highest physical capacity, but it is assigned a lower coordination index. The design directly tests whether a high capacity target can outperform a coordinated but slightly smaller deployment path.



**Figure 4. Battery cost projection and storage-capacity scenario design. Solid lines are public NREL cost projections; dashed lines are scenario capacity paths used to generate counterfactual model outputs.**

### Macroeconomic Effects

Figure 5 reports real GDP deviation, equivalent variation, electricity-cost index and carbon-emissions deviation relative to BAU. The interpretation is that coordinated storage increases effective VRE utilization and reduces electricity-cost pressure without requiring as much inefficient capital deployment as AHD. The coordinated allocation scenario generates the strongest welfare result among the storage scenarios. By 2035, CA increases real GDP by 0.42% and equivalent variation by 0.47% relative to BAU, lowers the electricity-cost index to 97.4

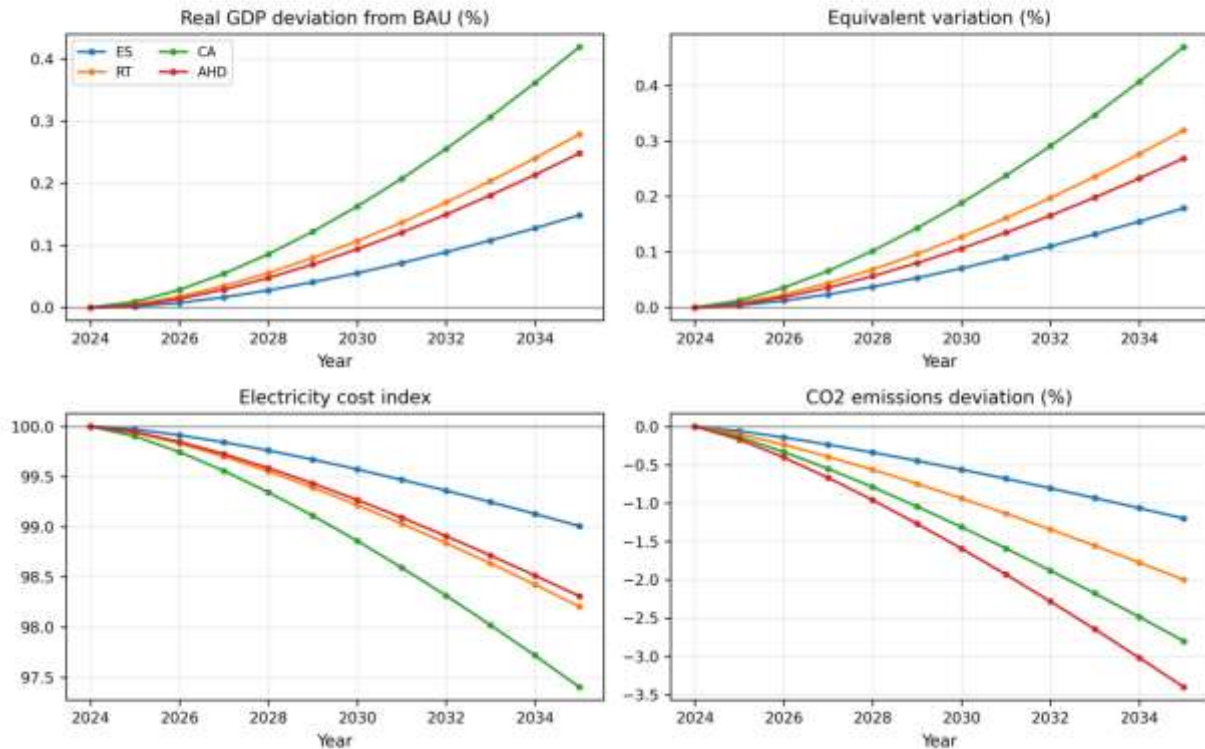
and reduces  $CO_2$  emissions by 2.8%.

The macroeconomic pattern is not a simple monotonic relationship between storage capacity and welfare. ES produces a positive but modest welfare gain because load-center storage reduces price pressure but does not fully address curtailment in resource regions. RT performs better because it directly raises the effective VRE utilization and reduces the wasted renewable output channel. CA performs best because it combines the resource-region curtailment reduction with load-center cost smoothing and interregional balancing. AHD installs more

capacity than CA, but its welfare gain is smaller because the marginal storage units are less effectively coordinated and a larger share of

investment resources is absorbed by storage construction rather than by other productive capital.

**Deterministic counterfactual macroeconomic outputs**



**Figure 5. Deterministic counterfactual macroeconomic outputs. All panels report model-generated deviations from BAU, except the electricity-cost index, which is normalized to 100 in BAU.**

Table 13 reports the 2035 endpoints. AHD installs 360 GW and 1440 GWh, more than CA, but its equivalent variation gain is only 0.27%. This is lower than the 0.47% gain under CA because weaker coordination makes part of the investment redundant from a system-balancing perspective. The result support a configuration-based

interpretation: the welfare value of storage depends on whether capacity is placed where it reduces curtailment and electricity-cost pressure. In this table, the table is placed directly in the main document so the key numerical outputs do not depend on an external table file.

**Table 13. Counterfactual 2035 model outputs relative to BAU.**

Scenario	Storage (GW)	Storage (GWh)	GDP dev. (%)	EV dev. (%)	Cost index	Curtailment (%)
BAU	160	512	0.00	0.00	100.0	8.2
ES	240	864	0.15	0.18	99.0	6.5
RT	280	1064	0.28	0.32	98.2	5.7
CA	320	1280	0.42	0.47	97.4	4.6
AHD	360	1440	0.25	0.27	98.3	4.2

**Table 14. Isolation checks for capacity, allocation and coordination effects in 2035.**

Counterfactual check	Storage	Allocation rule	Coordination	EV (%)	Purpose of the check
BAU reference	160 GW, 3.2 h	GDP-weighted	0.00	0.00	Reference path
Capacity-only expansion	320 GW, 4.0 h	GDP-weighted	0.35	0.20	Larger stock without coordinated placement
Allocation-only improvement	160 GW, 3.2 h	CA weights	0.75	0.12	Better placement with limited stock
CA allocation with low coordination	320 GW, 4.0 h	CA weights	0.35	0.33	Coordination loss under the CA allocation
Full CA case	320 GW, 4.0 h	CA weights	0.75	0.47	Central coordinated-allocation case
AHD case	360 GW, 4.0 h	Quantity-heavy weights	0.35	0.27	Higher capacity with weaker coordination
High capacity under CA rule	360 GW, 4.0 h	CA weights	0.75	0.49	Extra capacity under the coordinated rule

To be sure, CA performs best only because AHD is assigned a lower coordination index. To address this concern, Table 14 reports isolation checks around the central case. The checks are not statistical estimates; they are deterministic counterfactuals using the same reduced-form equations and parameter values. Capacity-only expansion improves EV relative to BAU, but less than full CA because storage is not placed and coordinated where its flexibility value is highest. CA allocation at the BAU capacity level improves welfare only modestly because physical storage capacity remains binding. A high-capacity case using the CA allocation and coordination rule produces slightly larger EV than the central CA case, but the increment is small relative to the extra storage investment. These checks support a narrower interpretation of the central result: coordinated deployment changes the welfare value of a given storage target, while capacity

expansion still has value when it is paired with effective allocation and dispatch coordination.

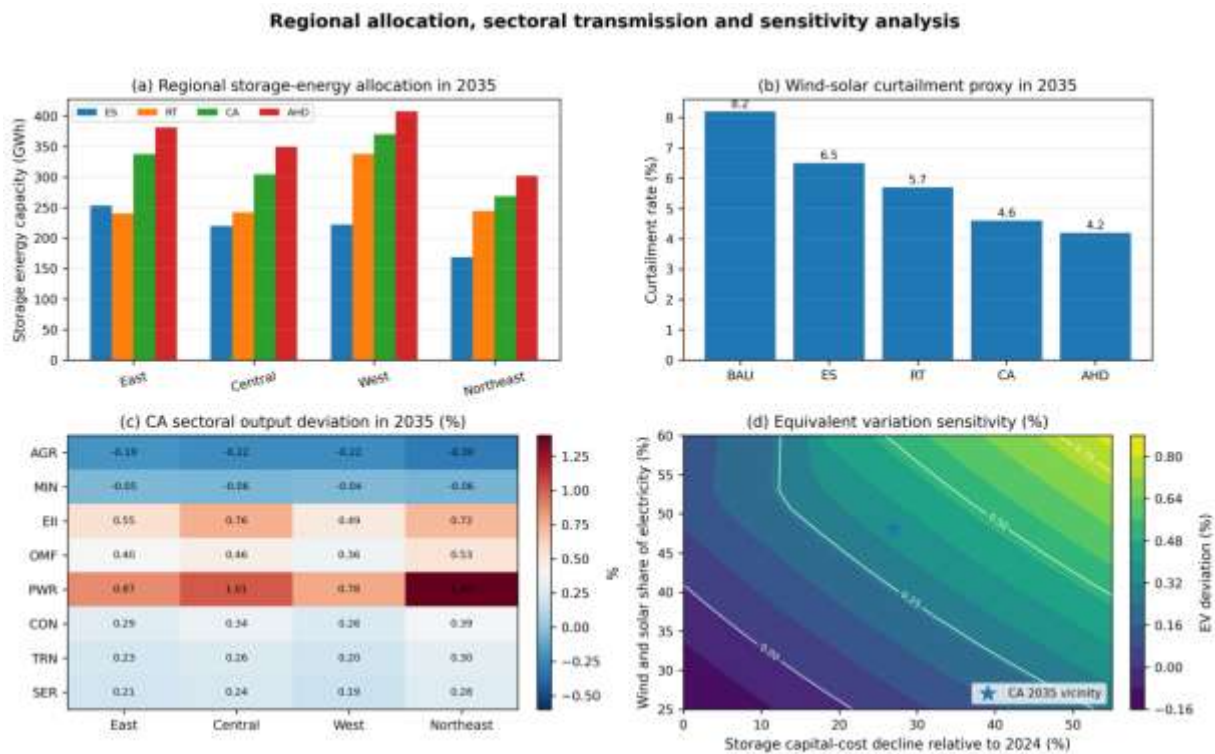
### Regional Allocation and Power-System Channel

Figure 6 reports regional storage-energy allocation, the curtailment proxy, sectoral output deviations and sensitivity. RT allocates more capacity to renewable-resource regions. ES allocates more storage to load centers. CA balances resource value, load value and connectivity. Under CA, the curtailment proxy falls to 4.6%, compared with 8.2% in BAU. AHD reaches a lower curtailment proxy of 4.2%, but it does so with substantially more storage and lower net welfare. This difference is economically important because it shows that the lowest curtailment rate is not necessarily the welfare optimum. The relevant criterion is whether the marginal cost of reducing curtailment is smaller than the macroeconomic benefit created by the

additional usable electricity.

The regional allocation channel also explains why storage affects sectoral output. Resource regions gain from higher effective renewable output and electricity-sector expansion. Load-center regions gain from lower electricity-cost pressure and smoother power-system operation. Regions with stronger connectivity gain additional balancing

value because storage services can substitute for more expensive local generation or network stress in other regions. In the compact model we represent these mechanisms through the allocation weights and curtailment equation rather than through an hourly dispatch model, but the qualitative interpretation is of course consistent with power-system economics.



**Figure 6. Regional allocation, sectoral transmission and sensitivity analysis. Panels (a)–(c) are deterministic 2035 model outputs; panel (d) reports sensitivity to storage-cost decline and wind-solar penetration.**

### Sectoral and Regional Transmission

The largest positive output effects in the sectoral results in Figure 6(c) are in electricity, energy-intensive manufacturing and other manufacturing. The mechanism is intuitive: lower electricity-cost pressure and lower curtailment increase the effective supply of electricity, and storage investment raises demand for equipment and construction services. Energy-intensive manufacturing benefits because electricity is an important intermediate input and because lower system-cost pressure improves competitiveness.

Other manufacturing benefits through equipment demand and lower power costs. Construction benefits from storage installation and grid related investment. Services gain modestly through higher real income and lower operating costs.

Economy-wide gains are accompanied by reallocation. Agriculture shows a slight negative output response because capital and intermediate inputs move toward storage related and manufacturing activities. This result is small but useful because it shows that the model is not imposing universal gains across all sectors. In a

full empirical implementation, this reallocation should be investigated with more detailed sector accounts and factor-market closes, because rural income, land use and regional labor mobility may alter the distributional result.

Regionally the West receives a strong electricity-sector gain because its higher VRE-potential index gives storage a high curtailment-reduction value. The East receives stronger manufacturing benefits because its load-center index is high and electricity-cost reductions are more valuable in dense industrial and service markets. Central China benefits from both load and balancing channel. The Northeast gains less because its lower GDP share and connectivity index reduce the allocation weight in the compact model. These regional differences support the main argument that storage configuration is a macroeconomic allocation issue rather than a uniform national capacity shock.

### Sensitivity and Robustness

In Figure 6(d) we see that welfare effects are nonlinear in storage cost and wind-solar penetration. At low wind-solar shares, additional storage has not much macroeconomic value, because at that point curtailment and peak-cost pressure is moderate. At high wind-solar shares, storage is valuable, but only if capital costs decline enough, so that it is not crowding out too much investment. The zero-welfare contour is

clearly a useful policy threshold: storage expansion is welfare improving, when the avoided electricity-system penalty is more than the annualized investment and crowding costs. This relationship is why storage can be economically valuable in one stage, of the energy transition and less valuable in another.

The parameter table and decomposition checks allow to do systematic robustness tests rather than only with the help of the visual sensitivity analysis. Table 15 reports the one-at-a-time perturbations around the central case. These are not statistical confidence intervals. They are, they are deterministic stress tests of the main ranking. Increasing the path of the storage cost weakens the GDP and the EV gains. Lowering  $b_{\kappa}$  in eq(13), reduces the benefit of storage because it means that less curtailment is avoided per unit of storage energy capacity. Lowering the coordination parameter, narrows CA advantage over RT and ES. Raising the elasticity of the substitution of electricity makes the economy less sensitive to the change of the electricity-cost induced by the storage, and lowering the elasticity increases the macroeconomic value of the flexibility. The central qualitative result is not changed: the coordinated allocation scenario gives a higher gain of the welfare than the accelerated high-deployment scenario in all the listed sensitivity cases.

**Table 15. Robustness checks for the 2035 equivalent-variation ranking.**

Sensitivity case	Parameter change	CA EV (%)	AHD EV (%)
Central case	Baseline assumptions	0.47	0.27
Low battery-cost path	$C^{\text{BESS}}$ lower path	0.61	0.40
High battery-cost path	$C^{\text{BESS}}$ higher path	0.29	0.09
Weaker curtailment response	$b_{\kappa}$ decreased by 20%	0.36	0.18
Stronger curtailment response	$b_{\kappa}$ increased by 20%	0.55	0.33
Lower coordination effect	$c_{\Omega}$ decreased by 20%	0.39	0.25
Higher coordination effect	$c_{\Omega}$ increased by 20%	0.55	0.30
Lower electricity substitution	$\sigma_{EL}=0.95$	0.53	0.29
Higher electricity substitution	$\sigma_{EL}=1.45$	0.41	0.25

These patterns are consistent with the literature on VRE integration costs and energy-economy model coupling [15,16].

## Discussion

### Policy Interpretation

Storage produces macroeconomic value when it reduces curtailment, lowers peak-cost pressure, supports interregional balancing and avoids excessive capital crowding. The results suggest that storage policy should not be evaluated only by installed capacity. A simple capacity target can produce a large physical deployment but a smaller welfare gain if storage is poorly coordinated with renewable bases, load centers and transmission conditions. The policy design should combine quantity targets with allocation rules, market incentives and dispatch coordination.

For China, this means that the storage planning should be linked with three policy dimensions. First, the storage near the renewable-resource base would change that otherwise curtailed wind and solar output into useful electricity. Second, the storage near the load center would reduce the peak electricity cost, and can also make industrial electricity price stable. Third, the cross region balancing rules and the transmission coordination make the value of storage increase, because the flexibility service in one region can reduce the cost elsewhere. These three dimensions are complimentary; if one only emphasizes one of them, it may produce a technically large but economically not efficient deployment path.

### Comparison with Existing Studies

The findings are consistent with the studies that VRE integration costs matter for the economy-wide outcomes [17,18]. They are also consistent with the evidence that the electricity nesting structures affect the CGE estimates of the renewable-curtailment policy in China [19]. Compared with storage-CGE work that is concerned with the national aggregates, the

contribution here is to frame the storage as a regional allocation problem and to show that the coordinated allocation can outperform the higher capacity deployment. The result is relevant for policy, because many of the storage targets are expressed in national GW terms, but the economic value of the storage is produced locally and regionally through curtailment, prices and trade.

The results also support the energy-system-CGE coupling logic of Nishiura *et al.* [20]. Note that the present paper does not solve an hourly dispatch model. Instead, it creates a transparent reduced-form bridge: storage changes effective VRE, curtailment, electricity cost and investment demand. These variables feed into the CGE accounting blocks. This bridge can later be replaced by the hourly dispatch outputs without changing the macroeconomic accounting structure. In that sense, the manuscript is positioned as a transparent scenario-screening implementation that can be expanded into a more detailed energy-system-CGE coupling exercise.

### Limitations and Future Implementation

The numerical results should be interpreted as a reproducible counterfactual experiment and policy-screening exercise, and not as an econometric estimate or an official forecast. The public anchors are observed data, but the regional allocation indices, compact IO coefficients, scenario paths and 2035 outcomes are calibrated model inputs or deterministic outputs. A full empirical implementation should replace the compact benchmark with a provincial SAM or MRIO table, sector specific taxes, interprovincial electricity trade data and an hourly power-system model. The present structure is chosen so that these should be replaced without re-writing the entire conceptual model.

A second limitation is that storage service is represented in annual-equivalent terms. This is appropriate for a CGE paper, but it cannot

substitute for unit-commitment or hourly dispatch. Future work should estimate Equation (13) from dispatch simulations under different wind, solar, hydro, thermal, storage and transmission conditions, and then pass the resulting coefficients into the MR-CGE model. The current paper should therefore be read as a reproducibility bridge toward a full energy-system--CGE implementation rather than as a claim that annual-equivalent storage variables can replace detailed dispatch analysis.

### Conclusions

This paper evaluates the macroeconomic costs and benefits of energy storage configuration in China using a storage-augmented multi-regional CGE framework. The central result is that storage deployment is welfare-improving only if the electricity-system value of storage exceeds its investment and crowding costs. More capacity is not necessarily better. In the deterministic counterfactual experiment [21,22], the coordinated allocation scenario produces a larger welfare gain than the accelerated high-deployment scenario despite installing less storage. This result is robust to the basic mechanism of the model: storage affects macroeconomic outcomes through curtailment reduction, electricity-cost smoothing, investment demand and interregional trade.

Three conclusions follow. First, public data anchors should be clearly separated from counterfactual model outputs. This distinction reduces the risk that reviewers interpret 2035 results as observed data. Second, storage policy should combine renewable-resource value, load-center value and interregional balancing value. Third, CGE models of renewable expansion should represent curtailment and storage explicitly; otherwise they may misstate both the cost and the benefit of high-renewable power systems [23,24]. The manuscript therefore provides a structured basis for a later full implementation using a provincial SAM, detailed

MRIO tables and dispatch-derived storage value coefficients [25,26,27].

### Supplementary Materials

The supplementary package includes CSV files for public anchors, sectoral calibration, regional indices, scenario endpoints, 2035 results, decomposition checks and robustness checks, together with a reproduction script for the numerical figures. The supplementary files preserve the same data-class labels used in the manuscript so that public inputs, calibrated inputs and counterfactual outputs are not conflated.

### Author Contributions

Conceptualization, A.W. and W.S.; methodology, A.W.; software, A.W.; validation, A.W. and W.S.; formal analysis, A.W.; writing—original draft preparation, A.W.; writing—review and editing, W.S.; supervision, W.S. All authors have read and agreed to the published version of the manuscript.

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### Institutional Review Board Statement

Not applicable.

### Informed Consent Statement

Not applicable.

### Data Availability Statement

The public anchors, calibrated model inputs, deterministic counterfactual outputs, decomposition checks, robustness checks, figures and numerical reproduction script are supplied as supplementary materials. Files labeled as calibrated inputs or counterfactual outputs should not be interpreted as observed statistics.

### Use of AI Tools

Figures 1 and 3 are schematic editorial diagrams and are not used as empirical evidence. They were redrawn as academic infographic-style schematic diagrams to clarify the model structure

and regional allocation logic. No conceptual figure is used as a data source or as a substitute for model output. The numerical figures and tables are based on public anchors, calibrated parameters and deterministic scenario rules.

### Conflicts of Interest

The author declares no conflict of interest.

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