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A CGE modeling framework with refined energy sector representation for energy strategy analysis in China

Binghao He* and Qin Wang

Energy Development Research Institute of China Southern Power, Guangzhou, China

* Correspondence author; E-mail: hebh@csg.cn.

Abstract: China's pursuit of carbon peaking and carbon neutrality is driving a profound transformation of its energy system, with increasing electrification and large-scale deployment of renewable energy. Traditional CGE models often aggregate energy sectors and overlook heterogeneous uses of energy, limiting their ability to analyze energy transition pathways and low-carbon policies. This study develops a CGE modeling framework with refined energy sector representation, disaggregating key energy activities and distinguishing fuel and material uses within a nested CES production structure. A benchmark-year Social Accounting Matrix for 2017 is constructed to calibrate the model. Simulations from 2017 to 2035 illustrate the framework's capacity to reproduce macroeconomic growth, capture the shift toward electricity-dominated energy use, and reveal sector-specific CO₂ emission reduction potential under stylized assumptions of labor and capital growth and a simple carbon pricing mechanism. By integrating detailed energy representation with economy-wide interactions, the proposed model offers a more realistic and policy-relevant tool for evaluating energy strategies and supporting China's low-carbon transition.

Keywords: CGE model; energy economics; energy strategy analysis.

1. Introduction

Under China's "dual carbon" goals of carbon peaking and carbon neutrality, the national energy system is undergoing a profound structural transition [1]. The traditional fossil-fuel-dominated energy system is being transformed toward a new structure characterized by large-scale deployment of renewable energy and deep electrification. In this process, the interactions among fossil energy, power systems, and renewable energy become increasingly complex, and energy transition is no longer a purely technological issue but a systemic transformation involving the entire economy [2].

Computable General Equilibrium (CGE) models provide a widely used and theoretically consistent framework for analyzing such economy-wide transitions [3]. By combining microeconomic behavioral foundations with macroeconomic accounting consistency and inter-sectoral linkages, CGE models are able to capture the joint adjustments of prices, quantities, and economic structures under policy and technology shocks, and are therefore well suited for integrated energy and climate policy analysis.



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However, most existing CGE models for China still suffer from important structural limitations inherited from the underlying input–output (IO) tables and Social Accounting Matrices (SAM). In particular, energy sectors are usually highly aggregated, such as combining oil and gas extraction into one sector and representing the power sector without distinguishing generation, transmission and distribution, or different generation technologies [4]. Moreover, different uses of energy commodities are typically treated uniformly as intermediate inputs, without distinguishing between fuel use with high substitutability and material use with very limited substitutability. These simplifications may distort price shock transmission, obscure technological substitution pathways, and lead to biased policy evaluation results, especially for power sector and renewable energy policies [5].

To overcome these limitations, it is necessary to enhance both the database structure and the behavioral representation of CGE models. On the one hand, the sectoral structure of the core database should be refined to explicitly represent key energy–related activities and commodities. On the other hand, the production structure should be redesigned to reflect the heterogeneity of energy uses and technologies, so that different substitution mechanisms can be properly captured within a unified general equilibrium framework [6].

Following this idea, this paper proposes an energy–transition–oriented CGE modeling framework for China. The main approach is to systematically disaggregate energy–related sectors based on the official input–output table and construct an extended SAM as the core database of the model, and to develop a multi–level nested CES production structure that explicitly distinguishes different types of energy uses. The proposed framework provides a more appropriate tool for analyzing energy transition pathways and energy strategy policies in a macro–consistent manner.

2. Methodology

2.1. Overview of the CGE model structure

The proposed modeling framework is built upon a standard static CGE structure, which represents the entire economy as a system of interdependent markets connected by consistent accounting identities and microeconomic behavioral equations [7]. In the benchmark equilibrium, all economic flows are recorded in a SAM, and model parameters are calibrated such that the benchmark solution exactly reproduces the base–year economic structure.

As illustrated in Figure 1, the CGE model consists of several interrelated modules, including the income–expenditure module, the investment–savings module, the commodity supply module, and the production module, which together determine prices and quantities in all markets.

The income–expenditure module describes the behavior of major economic agents, including households, enterprises, and the government. Households receive income from labor and capital, pay taxes, and allocate disposable income between consumption and savings. Household consumption behavior is modeled as utility maximization subject to a budget constraint, and the utility function is specified in a Cobb–Douglas form in this study [8]. Specifically, the representative household maximizes the following utility function:

$$U = \prod_i C_i^{\beta_i} \text{ subject to } \sum_i P_i C_i = Y_d \quad (1)$$

where C_i denotes the consumption of commodity i , P_i is its corresponding price, β_i is the share parameter satisfying $\sum_i \beta_i = 1$, and Y_d represents household disposable income. Solving this utility maximization problem yields the standard Cobb–Douglas demand functions:

$$C_i = \beta_i \cdot \frac{Y_d}{P_i} \quad (2)$$

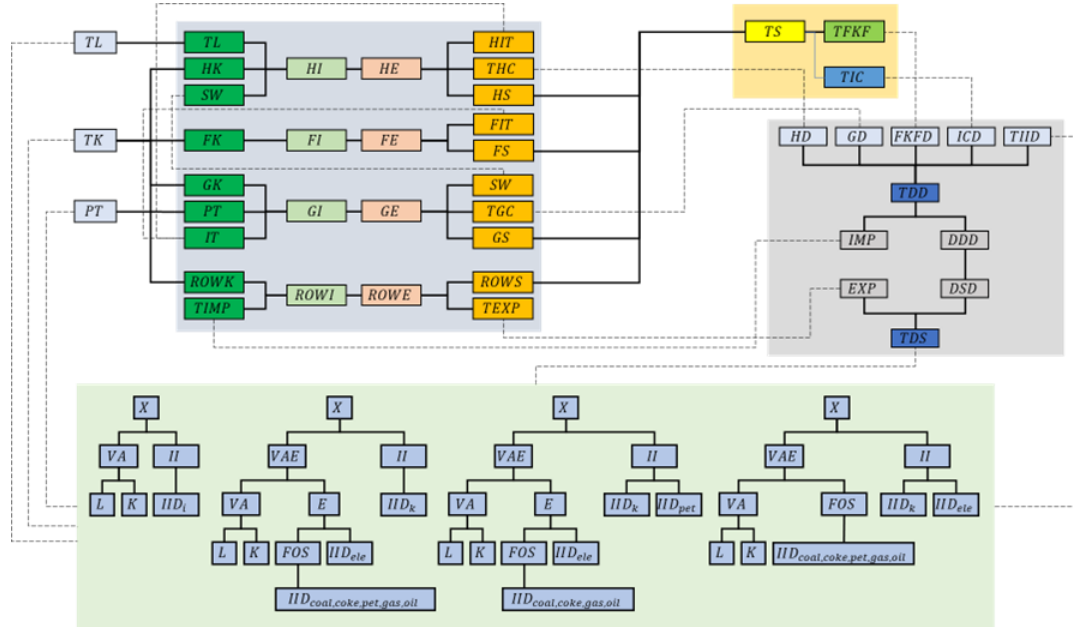


Figure 1. CGE model structure.

The investment–savings module follows a savings–driven closure, in which total investment is determined by the sum of savings from households, enterprises, the government, and the rest of the world. The allocation of investment demand across commodities follows fixed shares calibrated from the benchmark data.

The commodity supply module adopts the Armington assumption, under which domestic products and imported products are treated as imperfect substitutes [9]. Composite commodities are formed through a constant elasticity of substitution (CES) aggregation of domestic and imported goods, while domestic production is allocated between domestic markets and exports through a constant elasticity of transformation (CET) function [10]. Specifically, for each commodity i , total output X_i is allocated between domestic sales D_i and exports E_i according to:

$$X_i = (\theta_i^D \cdot D_i^{\phi_i} + \theta_i^E \cdot E_i^{\phi_i})^{\frac{1}{\phi_i}} \quad (3)$$

where θ_i^D and θ_i^E are share parameters and ϕ_i is the transformation parameter related to the elasticity of transformation.

The production module represents the core of the CGE model. In general, production activities are described by multi–level nested production functions, which combine intermediate inputs and primary factors to produce sectoral outputs. In this study, the overall modeling framework follows this standard structure, while the specific nested production structure, especially for energy–related sectors, will be further elaborated in the following subsection.

2.2. Construction of the social accounting matrix

A CGE model is essentially a system of parameterized behavioral and equilibrium equations, whose numerical solution depends critically on the calibration to a benchmark–year dataset. The SAM provides such a dataset by recording all economic transactions among production activities, commodities, factors, institutions, and the rest of the world in a consistent accounting framework. In a SAM, each account satisfies the fundamental identity that total income equals total expenditure, *i.e.*, the row sum equals the column sum [11].

Formally, a SAM can be represented as a square matrix S , where each element S_{ij} denotes the payment from account j to account i . For each account k , the following balance condition must hold:

$$\sum_i S_{ik} = \sum_j S_{kj} \quad (4)$$

In practice, a SAM is constructed by integrating multiple statistical sources, including the IO table, flow–of–funds accounts, and national statistical yearbooks. Among these data sources, the IO table plays a central role, since it provides the most detailed description of inter–industry production linkages and intermediate input structures, and therefore serves as the main basis for calibrating production functions in CGE models.

However, the officially available SAM or IO–based datasets for China exhibit important limitations for energy and climate policy analysis. In particular, energy–related sectors are highly aggregated: oil and natural gas extraction are combined into a single sector, and the power sector is not disaggregated into generation, transmission and distribution, nor into different generation technologies. Such aggregation prevents the model from representing the structural characteristics of the energy system and from capturing differentiated substitution mechanisms among energy technologies.

To address this problem, this study follows the method proposed in Reference [6] on disaggregated energy IO tables and constructs an extended SAM by systematically disaggregating energy–related sectors in the original IO table using external data sources. Specifically, sectoral splits are guided by information from energy balance tables, sectoral energy consumption statistics, and cost structure data of different energy technologies. Based on these auxiliary datasets, the original aggregated sectors are decomposed into multiple more detailed sectors, and a consistent disaggregated IO table is first obtained, which then serves as the core block for constructing the extended SAM.

Since the sectoral disaggregation is based on estimation and proportional allocation rather than direct statistical observation, the resulting preliminary SAM generally does not strictly satisfy the fundamental accounting balance condition, *i.e.*, row sums and column sums may not be exactly equal. Therefore, a balancing procedure is required to obtain a consistent SAM. In this study, a Maximum Entropy Tabular Reconciliation (METR) method, or called minimum information loss, is adopted to adjust the preliminary SAM [12].

Let $A = a_{ij}$ denotes the initial estimated SAM and $\hat{A} = \hat{a}_{ij}$ denotes the balanced SAM to be determined. The balancing problem is formulated as the following optimization problem:

$$\min_{x_{ij}} \sum_i \sum_j x_{ij} \ln \left(\frac{x_{ij}}{a_{ij}} \right) \quad (5)$$

subject to the accounting constraints:

$$\sum_i x_{ik} = \sum_j x_{kj}, \forall k \text{ and } x_{ij}, \forall i, j \quad (6)$$

2.3. Production module and nested CES structure with heterogeneous energy uses

The production module is the core component of a CGE model, as it describes the technological relationships of each production sector and largely determines how the entire economic system responds to price signals and policy shocks. The ability of a CGE model to realistically simulate structural change and substitution effects critically depends on whether the production functions can properly represent real-world production technologies and input substitution mechanisms.

In applied CGE modeling, multi-level nested CES production functions are widely adopted to describe sectoral production technologies [13]. In general, for a representative production activity j , output Q_j is produced by combining several composite inputs through a hierarchical nesting structure. A generic CES aggregation takes the following form:

$$X = \left(\sum_i \alpha_i \cdot X_i^\rho \right)^{\frac{1}{\rho}}, \rho = \frac{\sigma - 1}{\sigma} \quad (7)$$

where X_i denotes input components, α_i are share parameters, and σ is the elasticity of substitution. By stacking such CES functions in a nested structure, complex multi-stage production processes can be represented in a flexible yet tractable way. In this study, the production behavior of each sector is described as a profit maximization problem subject to a nested CES technology:

$$\max_{\{X\}} \Pi_j = P_j Q_j - \sum_i P_i X_{i,j} \text{ subject to } Q_j = F_j(X_{1,j}, X_{2,j}, \dots) \quad (7)$$

where P_j and P_i denote output and input prices, respectively, and $F_j(\cdot)$ represents the nested CES production function.

However, in conventional CGE models, the use of energy commodities in production is often treated in an overly simplified manner. Either energy goods are grouped together with other intermediate inputs and assumed to be substitutable in the same way, or all energy goods are separated into a single composite without distinguishing their different roles in production. In reality, within a given sector, energy commodities may serve both as fuels for combustion and as raw materials for production processes, and these two uses exhibit fundamentally different substitution characteristics.

To address this issue, this paper proposes a generic nested CES production structure that explicitly distinguishes different uses of energy commodities (shown in Figure 2). The overall production structure is organized as follows. At the top level, output is produced by combining a value-added composite and an intermediate-input composite. At the second level, the value-added composite is further decomposed into capital and labor, while the intermediate-input composite is decomposed into a material-input composite and a fuel-input composite. At the third level, the material-input composite consists of all non-energy commodities and the material-use part of energy commodities, whereas the fuel-input composite consists of all energy commodities used for combustion purposes.

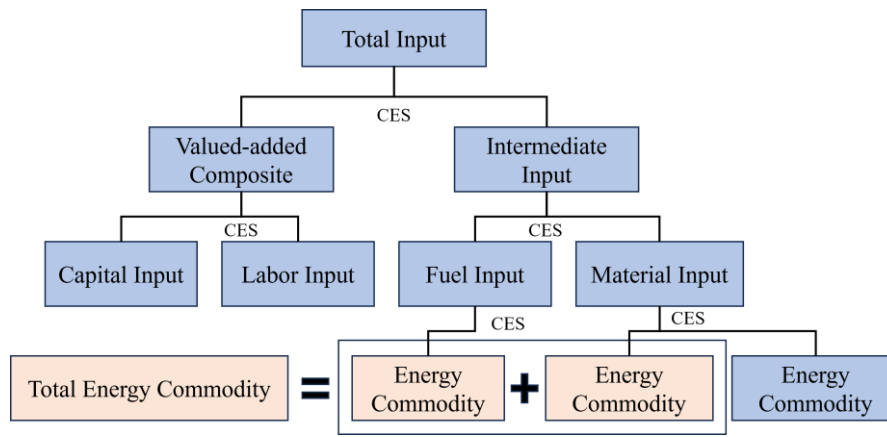


Figure 2. Nested production function structure.

Formally, for each sector j , the intermediate–input composite M_j is defined by a CES function:

$$M_j = (\alpha_j^{mat} \cdot MAT_j^{\rho_m} + \alpha_j^{fuel} \cdot FUEL_j^{\rho_m})^{\frac{1}{\rho_m}}, \rho_m = \frac{\sigma_m - 1}{\sigma_m} \quad (6)$$

where MAT_j and $FUEL_j$ denote the material–input composite and the fuel–input composite, respectively.

Under this structure, the benchmark–year input composition can be calibrated using information from the energy balance table. In particular, the shares of energy used as fuels and as materials in each sector can be obtained or inferred from sectoral energy statistics, and the benchmark SAM can be correspondingly adjusted to reflect the true physical use structure of energy commodities. This calibration ensures that the nested production functions are consistent with the actual technological characteristics of different sectors and provides a more realistic basis for simulating energy substitution and structural transformation.

3. Experiment

3.1. Settings

The CGE model uses 2017 as the benchmark year, with simulations spanning 2017–2035. The 2017 IO table is chosen over the 2022 table because the latter was affected by COVID–19 and may not represent typical economic conditions. The benchmark SAM integrates the 2017 national IO table, flow–of–funds accounts, statistical yearbooks, and energy statistics, providing a consistent basis for production, income, consumption, investment, and energy use.

To balance model complexity and computational tractability, the original 149–sector IO table is aggregated into 46 sectors [14], with disaggregation of crude oil and natural gas extraction and detailed power generation technologies, including coal, gas, hydro, wind, solar, and transmission and distribution [15].

The model incorporates two exogenous growth variables: capital stock, set at 5%, and labor supply, linked to population trends (3% for 2017–2025, 1% for 2026–2030, and –1% for 2031–2035) [16]. A simplified carbon pricing mechanism is introduced from 2020 onward, starting at 20 RMB/tCO₂ and growing at 5% annually. Sectoral carbon costs, calculated from fuel inputs and emission factors, are

included in production costs and transferred to the government sector, providing a stylized representation of China's low-carbon transition.

The elasticities of substitution in the nested CES production structure and Armington aggregation are calibrated based on a combination of existing CGE literature and empirical evidence for China. In general, higher substitution elasticities are assigned to energy-to-energy and fuel-mix nests to reflect relatively flexible technological choices, while lower elasticities are used for capital-labor and material-energy nests to capture stronger technological rigidity. All share and scale parameters are calibrated to exactly replicate the 2017 benchmark equilibrium, ensuring consistency between the model structure and the base-year SAM.

3.2. Settings

Figure 3 compares the real GDP observed in official statistics with the GDP predicted by the proposed CGE model. The model successfully reproduces the benchmark-year GDP in 2017, and generates a smooth projection for the subsequent years under the assumed capital and labor growth rates. The GDP trajectory indicates a continuous growth trend, reaching approximately 180.7 trillion RMB by 2035.

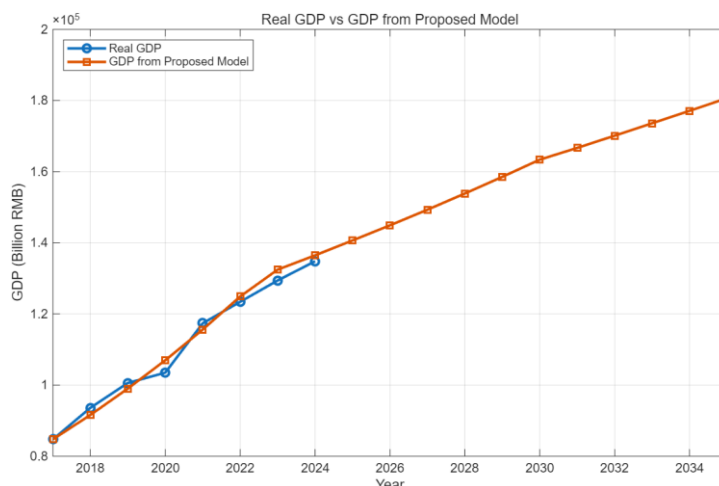


Figure 3. Comparison of real GDP and CGE model predicted GDP (2017–2035).

The comparison shows that the model slightly underestimates GDP in the early years and overestimates in the later years, reflecting the stylized assumptions on capital accumulation, labor supply, and simplified carbon pricing. Overall, the model captures the general macroeconomic growth pattern while providing a consistent framework for energy and emission analysis.

Figure 4 depicts the sectoral CO₂ emissions for 2017 and 2035. The results indicate a significant reduction in emissions across all major industrial sectors, including power generation, steel, cement, petrochemical, chemical, nonferrous metals, paper, and aviation. The largest absolute reduction occurs in the power sector, consistent with the increased deployment of low-carbon electricity generation. These results highlight the ability of the model to represent differentiated emission patterns and sector-specific mitigation potential. The evolution of China's energy consumption is also presented in Figure 4.

In summary, the proposed CGE framework successfully captures the economy-wide interactions between macroeconomic growth, energy transition, and emissions reduction. The results demonstrate

that disaggregating energy sectors and explicitly modeling heterogeneous energy uses provide richer insights into potential energy strategies and policy impacts in China.

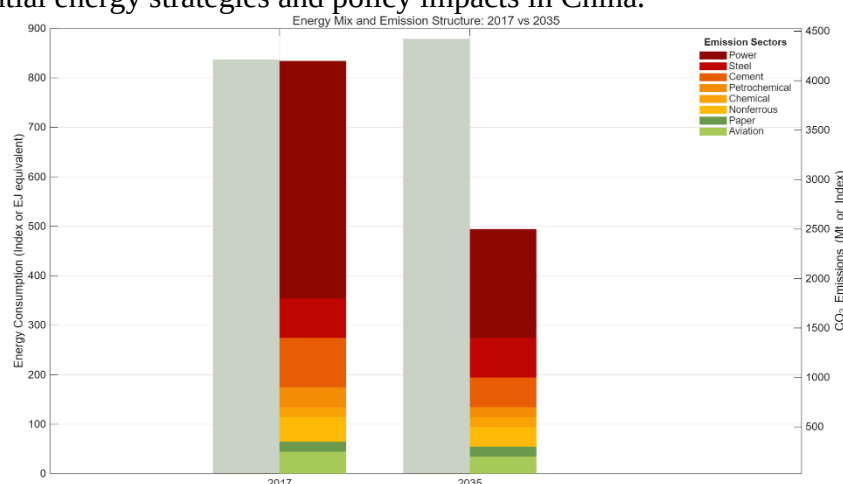


Figure 4. Energy Mix and Sectoral CO₂ Emission Structure in 2017 and 2035.

4. Conclusion

This study presents a CGE modeling framework with refined energy sector representation to support energy strategy analysis in China. By disaggregating key energy activities and distinguishing fuel and material uses within a nested CES production structure, the model overcomes limitations of conventional CGE approaches and provides a more realistic representation of the energy–economy interactions. Simulation results from 2017 to 2035 demonstrate the framework’s ability to reproduce macroeconomic growth, capture the transition toward electricity–dominated and low–carbon energy use, and highlight sector–specific CO₂ mitigation potential. The proposed framework offers a flexible and policy–relevant tool for evaluating energy transition pathways, informing low–carbon strategies, and guiding energy and climate policy design. Future work could extend this approach to incorporate more detailed technology learning, sectoral innovation, and stochastic policy scenarios to further enhance its applicability and predictive capability.

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Authors’ contribution

Conceptualization, methodology, validation, investigation, formal analysis, Binghao He; data curation, visualization, Qin Wang; writing—original draft preparation, writing—review and editing, Binghao He and Qin Wang. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

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