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Allocation of Total Building Energy Consumption in Liaoning Province from the Perspective of Equity and Efficiency

Sitong Dong*

School of Economics and Management, Dalian University of Technology, Dalian, China

**Corresponding author: Sitong Dong.*

Abstract

A sound allocation of building energy quotas is essential for implementing China's dual-control targets. This study projects Liaoning Province's total building energy consumption for 2020-2060 under the Shared Socioeconomic Pathways (SSPs) and defines the provincial conservation target as the difference between the 2060 projections under SSP2 and SSP1. A two-stage equity-efficiency allocation model is then developed. First, a composite indicator system covering energy-saving responsibility and potential is combined with CRITIC-TOPSIS to set initial quotas for the 14 prefecture-level cities. Second, an input-oriented zero-sum-gains DEA (ZSG-DEA) model redistributes the quotas without changing the total until every city attains unity efficiency. The saving target is 15.484 billion kgce. After optimisation, Dalian, Panjin and Shenyang receive the largest quotas, jointly 27.68% of the total, whereas the other cities cluster within a narrow range owing to similar energy-consumption structures. The framework provides a reference for allocating building energy quotas in Liaoning and a transferable approach for other Chinese provinces.

Keywords

building energy conservation potential, total building energy consumption allocation, CRITIC-TOPSIS, ZSG-DEA, Liaoning Province

1. Introduction

Limiting global warming and curbing energy consumption are shared international objectives. As the world's largest energy consumer and carbon emitter [1], China has pledged to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060. Liaoning, a traditional heavy-industrial base with a fossil-fuel-dominated energy mix, is critical to delivering these goals: its building energy consumption reached 59.597 Mtce in 2021, ranking sixth nationwide (CBEED). Controlling building energy use while safeguarding development and exploiting conservation potential is therefore of strategic importance.

A defensible provincial cap is the basis of sectoral conservation, and its allocation among prefecture-level cities is a prerequisite for quota setting [2]. Liaoning's current policies remain oriented towards performance indicators such as green buildings and retrofits, with little analysis of achievable savings under the dual-carbon pathways; conservation policy is thus decoupled from conservation potential. A shift from efficiency improvement to total-quantity control is required, together with a scheme that reconciles equity

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(accommodating regional disparities and legitimate demand growth) with efficiency (exploiting differences in energy performance). Uniform targets and locally self-reported quotas are unsuitable here.

Combining equity and efficiency is increasingly recognised as decisive. Wang and Chen [3] show that an equity-only rule penalises high-performing regions while an efficiency-only rule induces a Matthew effect; Guan and Zhang [4] demonstrate that composite criteria outperform single ones. Existing methods comprise indicator-based approaches, DEA models and game-theoretic models [4-6]: Li et al. [5] coupled the Shapley value with ZSG-DEA in a two-step CO2 quota scheme, and Tan et al. [6] combined equity indicators with ZSG-DEA optimisation. Yet most studies allocate at national, provincial or sectoral level, and scenarios rarely link demographic, economic and technological factors to policy through SSPs. This study projects Liaoning's building energy consumption to 2060 under the SSPs and allocates the saving target among its 14 cities with a two-stage equity-efficiency framework.

2. Data and Methods

Data are drawn from the China Statistical Yearbook, the statistical yearbooks of Liaoning and its cities, population census yearbooks, and the China Building Energy Consumption and Carbon Emission Research Reports for 2016-2023.

2.1 Projection of Building Energy Consumption, 2020-2060

Total building energy consumption is decomposed as:

$$E = EI \times S \times P \tag{1}$$

where E is total building energy consumption, EI energy use per unit floor area, S per capita floor area and P population. Population is projected by the cohort-component method [7], which generates pathway-consistent variants unlike the Leslie matrix [8], probabilistic [9], logistic [10], grey [11,12] and neural-network [13] alternatives. Starting from the seventh census with five-year age groups, fertility, mortality and migration follow the IIASA-SSP assumptions for China; the sex ratio at birth converges to 105 by 2030. Per capita floor area is capped by comparison with developed countries [14,15] rather than extrapolated: urban and rural residential areas peak at 33 m² and 38 m² (annual increments of 0.2333 m² and 0.3 m² after stabilisation), while public-building area remains 0.22 m² per capita.

Energy intensity is projected by combining the extended IPAT framework [16] with SSP narratives [17]; population density p, per capita GDP g and energy intensity per unit GDP e are its principal determinants, estimated as

$$\ln EI = \ln A + \alpha \ln p + \beta \ln g + \gamma \ln e \tag{2}$$

where A is constant and α, β and γ are parameters. GDP growth rates follow the provincial Fourteenth Five-Year Plan and Leimbach et al. [18], Zhang and Wang [19] and Niu et al. [20]; population density is the reciprocal of projected floor area per capita; energy intensity per unit GDP follows Dong et al. [21]. SSP1 assumes low fertility, low mortality, medium migration, high GDP growth and low energy intensity; SSP2 assumes medium values throughout; SSP3 assumes the reverse of SSP1; SSP4 and SSP5 complete the scenario space.

2.2 Two-Stage Allocation Model

Following Huang et al. [22], the target is allocated in two stages: CRITIC-TOPSIS sets initial quotas from a composite indicator system, and input-oriented ZSG-DEA then reallocates them until every decision-making unit (DMU) is efficient.

Four indicators span two dimensions (Table 1). Responsibility is represented by energy intensity per unit GDP (x1) and historical energy intensity per capita (x2), since developed regions with higher historical use bear greater responsibility [23]; potential by patent grants per capita (x3) and the tertiary-industry share of GDP (x4), which capture technological decoupling. All four are negative indicators. Electricity consumption proxies energy intensity for data completeness and because it exceeds 35% of terminal building energy use and is rising [24].

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Table 1: Indicator system for the initial allocation of building energy quotas.

Dimension	Indicator	Symbol	Attribute
Responsibility	Energy intensity per unit of GDP (annual average)	x1	Negative
Responsibility	Historical energy intensity per capita (annual average)	x2	Negative
Potential	Patent grants per capita (annual average)	x3	Negative
Potential	Share of tertiary industry in GDP (annual average)	x4	Negative

For a negative indicator the matrix is normalised as $z_{ij} = (\max_j x_j - x_{ij})/(\max_j x_j - \min_j x_j)$. CRITIC weights combine the standard deviation σ_j and the correlation r_{jk} between indicators:

$$C_j = \sigma_j \Sigma_k(1 - r_{jk}), \quad w_j = C_j / \Sigma_j C_j \tag{3}$$

With $v_{ij} = w_j z_{ij}$, the distances D_i^+ and D_i^- to the positive and negative ideal solutions give

$$C_i = D_i^- / (D_i^+ + D_i^-), \quad 0 \le C_i \le 1 \tag{4}$$

Normalising C_i to a unity sum gives the initial quota shares. The total to be distributed comes from the SSP1 projections, which represent a stringent net-zero-compatible target.

Because efficiency is central to allocation [25], ZSG-DEA evaluates and iteratively improves the stage-one scheme, reallocating inputs without changing their total until all DMUs reach a common efficient frontier. Energy consumption is the sole input (undesirable outputs treated as inputs); GDP and population are desirable outputs. For DMU r:

$$\min \theta_r \quad \text{s.t. } \Sigma_t \varphi_t e_t \le \theta_r e_r, \quad \Sigma_t \varphi_t y_{ts} \ge y_{rs}, \quad \Sigma_t \varphi_t = 1, \quad \varphi_t \ge 0 \tag{5}$$

where θ_r is relative efficiency, φ_t the weight of DMU t, e_t its allocable input and y_{ts} its s-th output, with $\Sigma_t e_t' = \Sigma_t e_t$ at every iteration. Quotas are adjusted until $\theta_r = 1$ for all cities.

3. Results and Discussion

Substituting the projected population, floor area and energy intensity into Equation (1) gives building energy consumption under each pathway. SSP1 is calibrated to the net-zero-compatible sustainable objective and SSP2 to the current trajectory; their 2060 difference is the provincial conservation target, 15,483,762,747 kgce (approximately 15.484 billion kgce).

CRITIC-TOPSIS assigns the largest shares to Jinzhou, Dandong and Tieling (nearly 30% combined) owing to high historical energy intensity per capita, and the smallest to Anshan and Yingkou (9.11%), reflecting low development and low energy use per unit GDP. Shenyang ranks tenth with 6.17%; despite high energy efficiency, such a low quota would constrain its development, illustrating the limitation of an indicator-based allocation that disregards output efficiency.

Only Shenyang, Dalian and Anshan initially attain unity efficiency, whereas Jinzhou, Tieling and Dandong score about 0.5 (Table 2). Iterative ZSG-DEA raises all scores to 1 on a unified efficient frontier, confirmed by a conventional DEA calculation. Efficient cities such as Dalian and Shenyang gain quota, while initially inefficient ones such as Jinzhou and Tieling lose quota, incentivising energy restructuring and stronger management.

Table 2: Initial and final building energy quotas and efficiency scores of the 14 prefecture-level cities (10^4 kgce).

City	Initial quota	Initial efficiency	Final quota	Final efficiency
Shenyang	95542.57	1.00	142306.16	1.00
Dalian	96329.29	1.00	143477.94	1.00
Anshan	67500.60	1.00	100538.96	1.00
Fushun	110544.06	0.63	100538.96	1.00
Benxi	85906.46	0.86	109417.69	1.00
Dandong	134997.46	0.52	100538.96	1.00
Jinzhou	141291.17	0.50	100538.96	1.00
Yingkou	73597.83	0.96	105298.19	1.00
Fuxin	130553.10	0.54	100538.96	1.00
Liaoyang	100375.80	0.69	100681.57	1.00
Panjin	128865.19	0.76	142883.04	1.00
Tieling	138712.33	0.51	100538.96	1.00
Chaoyang	125109.69	0.56	100538.96	1.00
Huludao	119050.73	0.59	100538.96	1.00

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Dalian, Panjin and Shenyang obtain the largest final quotas, jointly 27.68% of the total; the other cities cluster between 100,000 and 110,000 × 10^4 kgce. Shenyang and Dalian need larger allowances to sustain growth despite high historical consumption; Panjin, a designated petrochemical base and a key city of the coastal economic belt, needs a substantial allowance for its distinctive industrial structure. The similarity of the remaining quotas reflects comparable energy-consumption structures and small differences in saving responsibility and potential.

4. Conclusions and Policy Implications

Building energy consumption in Liaoning for 2020-2060 is projected under the SSPs by combining a cohort-component population model, peak-based floor-area projection and an IPAT-SSP energy-intensity model, from which the provincial conservation target is derived. A two-stage framework then allocates it. In stage one, equity and efficiency are represented by four indicators of saving responsibility and potential, and CRITIC-TOPSIS gives larger initial quotas to Jinzhou, Fuxin, Tieling and Dandong and smaller ones to Anshan, Yingkou, Benxi and Shenyang. In stage two, ZSG-DEA reallocates quotas towards efficiency while preserving the total and regional heterogeneity until all 14 cities reach an efficiency of 1. The final scheme gives larger quotas to Shenyang, Dalian and Panjin and nearly uniform quotas elsewhere.

Two implications follow. First, municipal quotas should be set through a two-stage procedure: Liaoning's fossil-dependent economy needs both conservation obligations and sufficient energy space for development, which the framework secures while improving system efficiency. Second, differentiated schemes should reflect local economic conditions and resource endowments, with optimised resource allocation, expanded technology supply and new energy development to adjust the energy mix. Although quotas differ little outside the three leading cities, differentiation remains necessary to exploit each city's conservation potential and to support the dual-carbon targets.

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Conflicts of Interest

The author(s) declare no conflicts of interest.

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