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SPECIAL FEATURE: ORIGINAL ARTICLE

Natural capital accounting for sustainable cities

Impacts of low-carbon transition on human capital and future sustainability via electricity market: a framework based on inclusive wealth analysis at the regional level in China

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Abstract

The Sustainable Development Goals (SDGs) set the agenda for future development, with economic, environmental, and social sustainability as the three pillars of sustainability. Achieving the SDGs requires understanding the combined impact of current policies over time. The Inclusive Wealth (IW) Index integrates economic, environmental, and social dimensions, providing a comprehensive tool for assessing sustainability at the regional level. However, its use in forecasting future sustainability trends is limited, restricting its applicability in guiding long-term policy development. Developing countries, particularly those reliant on coal-fired power generation, face the dual challenges of promoting economic growth while mitigating the impacts of climate change. Renewable energy (RE) offers a potential solution to reduce carbon emissions, but it also presents economic and infrastructural challenges. This study proposes a new framework that combines the computable general equilibrium and Greenhouse Gas-Air Pollution Interactions and Synergies models to estimate future sustainability under the IW framework, focusing on RE development, air pollution alleviation, and carbon emission abatement. Using Shandong Province as a case study, the framework provides a comprehensive assessment of the impacts of RE development on the economy, carbon damage, and health capital. Our results indicate that carbon pricing can increase reliance on electricity transmission for the low-carbon transition, while local RE replaces local thermal power to some extent. The findings show that the development of RE and domestic electricity transmission positively impacts GDP, air pollution alleviation, carbon abatement, and human health capital, which can be further accelerated by carbon tax policies. The co-benefit of air pollution reduction and carbon abatement provides valuable insights for policymakers, suggesting that policies promoting energy structural shifts may be beneficial for sustainable development.

Keywords Renewable energy · Induced technological change · Human capital · Carbon tax policy · Future sustainability

Introduction

Sustainable development is a global consensus for the advancement of human society. Agenda 21 emphasized the need for development paths that safeguard the needs of both present and future generations. The United Nation's Sustainable Development Goals (SDGs) for 2030 aim to address critical issues such as poverty, inequality, and climate change. The establishment of these goals underscores the global community's commitment to a sustainable future and guides our collective efforts (Purvis et al. 2019). Achieving these goals requires a comprehensive understanding of how current actions impact future sustainability. Therefore, framing future sustainability can help identify whether a state

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is meeting population needs and assess the future impact of current policies and actions, ultimately supporting the development of long-term strategies.

Traditional economic indicators, such as GDP, only reflect a region's economic development. However, sustainability requires measuring whether development meets the needs of future generations without compromising present needs, as proposed by the World Commission on Environment and Development in 1987. The Inclusive Wealth (IW) Index, featured in UN reports such as those from the United Nations Institute for Environmental Research (UNIEP), integrates economic, environmental, and social factors (Kurniawan et al. 2021; Managi and Kumar 2018a). The IW Index defines sustainability as the aggregate value of natural capital, human capital, and produced capital, representing natural resources, human well-being, and fixed assets, respectively (Engelbrecht 2016). By integrating these three dimensions, the IW Index offers an important tool for assessing sustainability levels. The IW index, incorporating human, produced, and natural capital at the provincial and city levels, has been studied using historical data and econometric methods (Wang et al. 2020a). While the IW Index can comprehensively evaluate regional sustainability based on past data, previous studies lack an estimate of health capital impacted by environmental policies (Cheng et al. 2022).

Although the economy remains central to future development, as "No Poverty" is the first SDG goal, environmental considerations should also be factored into future sustainability estimates. In light of increasingly severe global climate change, developing countries are also facing a serious carbon peak situation (Kaygusuz 2012; Zhao et al. 2022). Sustainability can be enhanced by renewable energy (RE) development, as it reduces reliance on fossil fuel extraction. This transition promotes cleaner energy consumption, drives economic growth, and minimizes the environmental costs associated with resource depletion (Huo et al. 2024). However, the higher costs and intermittency of RE compared to traditional fossil fuels pose challenges in fossil fuel-dependent regions. Furthermore, uncertainty surrounding technological advancements, energy markets, and geopolitical conditions further hinders RE development, affecting the growth of natural and produced capital (Yamaguchi and Managi 2019).

The undeveloped RE sector has become a barrier to future sustainability. To address the dilemma of energy transition, many countries have implemented environmental regulations to promote RE development and phase out thermal power. Technological innovations have contributed to a decrease in the cost of RE, a trend likely to continue (Tian and Zhang 2023). Ortega et al. (2020) found that the skills and education levels of workers in the RE sector, particularly in wind and solar energy, significantly influence technological progress. Acemoglu et al. (2012) proposed the concept of induced technological change (ITC), which suggests that environmental policies can lead to the substitution of cleaner products for dirtier ones through endogenous technological innovation. One application of ITC, learning-by-doing (LBD), has been shown by He et al. (2022) to benefit from public research and development policies in the RE sector. Guo and Fan (2017) examined the learning rate of optimal new abatement technologies.

The development of RE plays a key role in both the improvement of produced capital and human capital. While RE may require higher short-term investments, placing pressure on local finances (Tu et al. 2019), long-term benefits include substantial health and environmental improvements. Reduced air pollution directly benefits human well-being, thereby positively affecting human capital in IW (Li and Managi 2022; Zhang et al. 2023b). Furthermore, carbon emission abatement is linked to air quality improvements, with reduced $PM_{2.5}$ emissions resulting in lower health economic losses (Jia et al. 2023).The reduction in $PM_{2.5}$ is likely to foster technological innovation and increase knowledge stock through human capital accumulation (Wang and Wu 2021). The GAINS model suggests that the effects of $PM_{2.5}$ on health are highly localized carbon emissions from Tibet in the northeast have minimal impact on health conditions in eastern coastal provinces in China (Xie et al. 2018). Therefore, policies targeting carbon emission abatement and RE development are likely to reduce health expenditures at the city or provincial level, particularly for respiratory diseases (Xie et al. 2016). These savings could potentially be redirected toward education, thus increasing human capital (Frankovic and Kuhn 2023). The GAINS model plays a critical role in evaluating regional health impacts of environmental factors.

Given that the impact of carbon emissions on health should be assessed at a regional scale, this research will focus on regions with heavy industrial and dirty energy structures. However, these regions are typically economically underdeveloped and face challenges in adopting RE, as the high cost of RE may hinder its development (Aziz and Bakoben 2024). In addition, the intermittency of RE results in high storage costs, further limiting its supply stability (International Renewable Energy Agency 2022; Kim and Jung 2018). To foster RE development, governments should implement policy instruments, necessitating future scenario analyses to measure sustainability (Zander 2021). Carbon-related policies, particularly those aimed at reducing carbon emissions, can improve health by addressing air pollution, with the decommissioning of coal-fired power plants playing a pivotal role (Zhang et al. 2023a). Although carbon taxes, a form of command-and-control regulation, may lead to GDP losses due to increased energy prices, previous studies, including Helm and Mier (2021), highlight the importance of carbon taxes for carbon abatement in China. Moreover, reliance on domestically imported electricity should be considered in regional industrial transitions under carbon pricing, as power transmission can alleviate low-carbon transition pressures (Tan et al. 2022). Regions with higher reliance on thermal power may require more electricity transmission, as the increased penetration of RE can raise electricity prices for energy-intensive industries (Deng et al. 2023).

While past studies have focused on historical sustainability assessments, a gap remains in predicting future sustainability trajectories. Most models, such as Computable General Equilibrium (CGE) and Integrated Assessment Models (IAM), have concentrated on economic and environmental aspects, largely neglecting social dimensions such as well-being and health (Böhringer and Löschel 2006). For example, Wang et al. (2020b) combined CGE with other models to assess global economic losses (GDP) from climate change, and Xie et al. (2016) evaluated medical expenditure changes caused by climate change and air pollution. However, few studies have directly measured sustainability changes. Raviv et al. (2024) explored sustainability in agriculture using CGE and IAM, yet comprehensive sustainability evaluations remain scarce. The IW index has assessed sustainability in over a 100 countries using historical data but lacks the ability to predict future sustainability trajectories. To truly understand the impact of current policies on sustainability, a future-oriented framework is required one that incorporates predictive capabilities to estimate future sustainability based on the IW index. This study aims to bridge this gap by integrating CGE and GAINS models to forecast changes in human capital, environmental benefits, and produced capital at the regional level.

The primary objective of this research is to develop a comprehensive framework for analyzing future sustainability. The preliminary future IW estimation framework aims to quantify and predict the impact of low-carbon policies on human health, produced capital, and carbon damage, all under the IW framework. This estimation is proposed due to the lack of a systematic and mature method for estimating natural capital, such as timber and fisheries, based on flow results from CGE and GAINS models. Unlike previous research that uses CGE and GAINS models to analyze the flow of monetary losses due to air pollution or applies the IW index for historical sustainability calculations, this study uniquely contributes by providing a comprehensive assessment of the future impacts of RE development on sustainability within the IW framework. This approach considers not only economic factors but also environmental benefits and human capital. Through this framework, we aim to gain insights into the complex relationship between RE development, human capital improvement, and future sustainability, offering policy implications for achieving the SDGs at both regional and national levels.

Methodology

Overall framework

The basic production, marketing, income, and expenditure are simulated using a CGE model with LBD module in the RE power sector. This research employs a CGE model for Shandong province, with the rest of China treated as exogenous. To incorporate the health impacts of RE development, this paper combines the CGE model with the GAINS-China model (Fig. 1). The GAINS-China model is a version of the GAINS model tailored with Chinese data inputs, capable of calculating annual average $PM_{2.5}$ concentration at both the province and city levels. Lin et al. (2023) link the GAINS and CGE models to assess the economic impacts of carbon capture and storage technology on energy transition and carbon reduction, outlining the pathways to carbon neutrality and the associated socio-economic benefits at the provincial level.

China's updated Nationally Determined Contribution (NDC) for 2030 aims to increase the share of non-fossil energy consumption in total primary energy to 25% and to peak carbon emissions. There is no doubt that China's future sustainability will heavily depend on investments in RE. Therefore, the construction of a future-oriented sustainability under IW framework can provide a comprehensive assessment of the multi-dimensionality of RE development. Shandong, the largest carbon emitter at the provincial level in China, faces significant challenges in reducing carbon emissions to meet the national carbon peak target, yet it also has substantial potential for RE development. Shandong Province's cumulative installed capacity of photovoltaics is approximately 73 gigawatts (GW), ranking first in China. Its cumulative installed capacity of wind power is around 27 GW, ranking fifth in the country, while the installed capacity of new energy storage is about 15.5 gigawatt hours (GWh), ranking third nationwide. Furthermore, this research estimates sustainability from 2025 to 2050, considering the phase-out of thermal power plants in Shandong province (Wu et al. 2024). Therefore, Shandong serves as an appropriate case study for analyzing future sustainability in the context of carbon reduction and pollution abatement. In addition to estimating sustainability

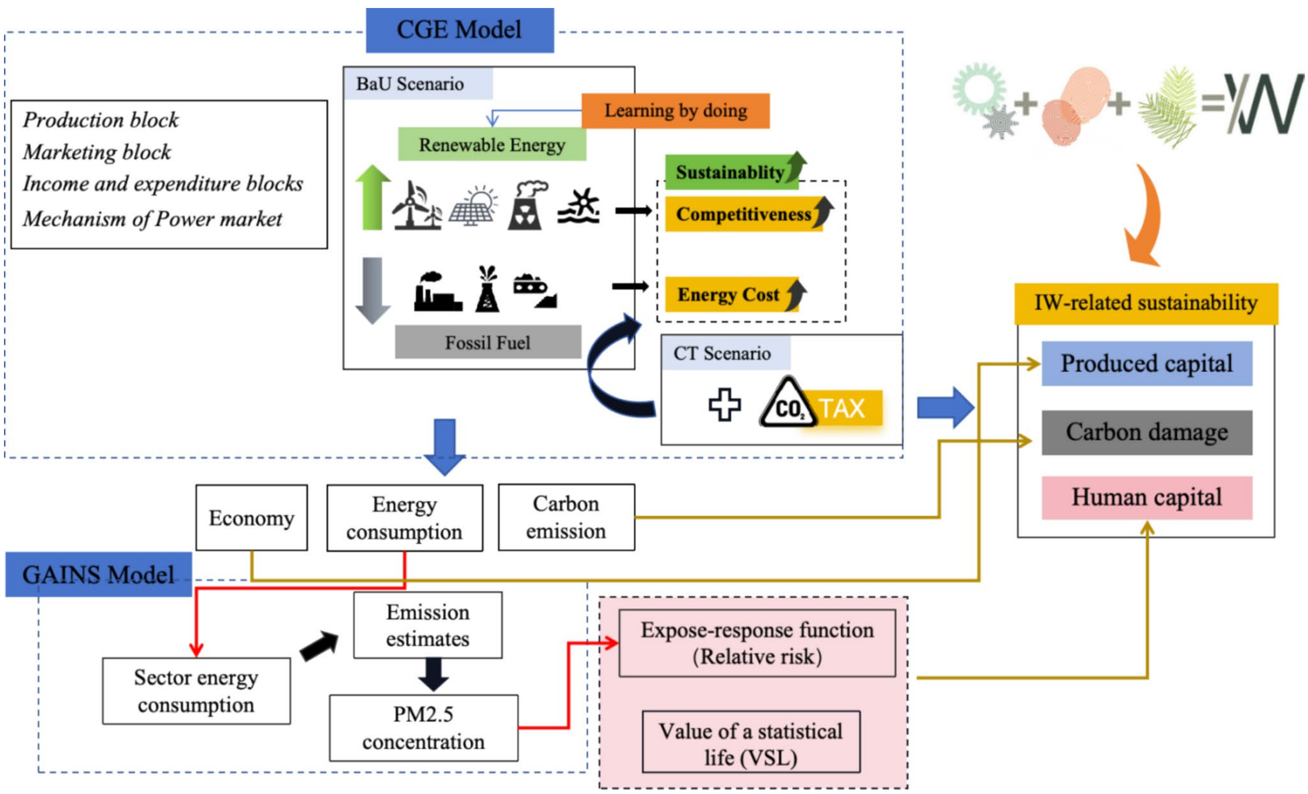


Fig. 1 Framework diagram of the integrated assessment model

under the IW framework from 2025 to 2050, natural capital is excluded, as both the GAINS and CGE models are unable to estimate the extraction of metals, minerals, etc. We avoid overestimating the impact of reduced fossil fuel extraction on sustainability under the IW framework, as carbon damage and health capital can be represented by the reduction in fossil fuel consumption. Our research focuses on estimating produced and human capital.

CGE model

The CGE model is established as shown in Fig. 2, based on our previous work. The industrial production block governs the production activities of all sectors, the marketing block manages domestic sales, exports, and imports, the expenditure block describes the consumption behaviors of households and government, and the income block accounts for labor and capital payments to households and tax collection by the government. Finally, LBD mechanism is incorporated into the RE generation and storage in the production block of the power sector. The industry classification is shown in Table 1.

Production block

In this research, all industries adhere to the zero-profit condition, as shown below:

$$\begin{aligned} \mathrm{PX}_c \times \mathrm{QX}_c\left(1-\mathrm{tp}_c\right) = {} & \mathrm{PL}_c \times \mathrm{QL}_c + \mathrm{PK}_c \times \mathrm{QK}_c \\ & + \sum_{\mathrm{ECC}} \mathrm{QA}_{\mathrm{ecc},c} \times \mathrm{PQ}_{\mathrm{ecc}} \\ & + \sum_{\mathrm{NEC}} \mathrm{PQ}_{\mathrm{nec},c} \times \mathrm{QA}_{\mathrm{nec},c} \\ & + \mathrm{tco} \times \sum_{\mathrm{ECC}} \mathrm{ENCO2}_{\mathrm{ecc},c} \mathrm{QA}_{\mathrm{ecc},c} \end{aligned} \quad (1)$$

$C = \{\text{all the sectors}\}$ and $c \in Candi \in C$,
$\mathrm{ECC} = \{\text{all the energy sectors}\}$ and $\mathrm{ecc} \in \mathrm{ECC}$;
$\mathrm{NEC} = \{\text{all the non}-\text{energy sectors}\}$ and $\mathrm{nec} \in \mathrm{NEC}$.
where PX is the output price of commodity c. PL, QL, PK, and QK represent the price and quantity of labor and capital input for the production of commodity c, respectively. PQ and QA represent the price and quantity of intermediate inputs, respectively. tp and tco are the production tax and carbon tax on the production of commodity c. $\sum_{\mathrm{ECC}} \mathrm{ENCO2}_{\mathrm{ecc},c}\mathrm{QA}_{\mathrm{ecc},c}$ is the carbon emission of production commodity c. The Eq. (1) indicates that all industries maximize their profits using a Constant Elasticity of Substitution (CES) function.

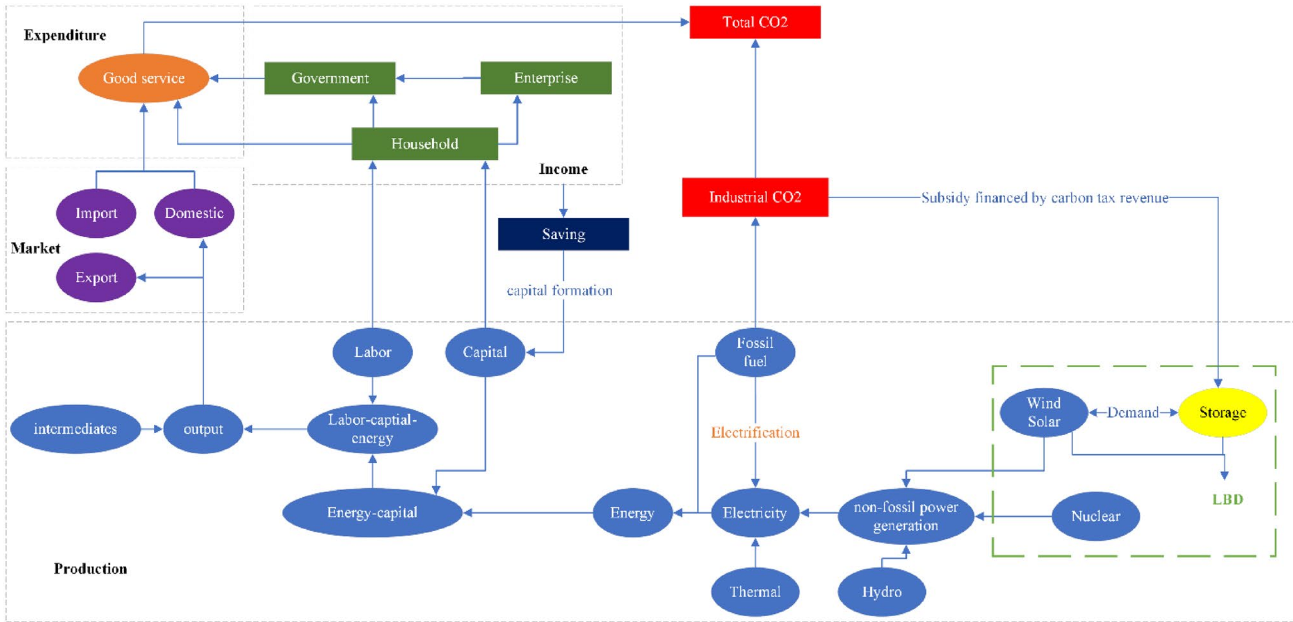


Fig. 2 Framework of CGE model (Shi et al. 2023)

Marketing block

The marketing block describes the export, import, and domestic sales of all commodities as shown below:

$$\mathrm{QM}_c = \left(\frac{\delta_c^m}{\delta_c^{dm}} \times \mathrm{PD}_c/\mathrm{PM}_c\right)^{\sigma_c^m} \mathrm{QD}_c, \tag{2}$$

Table 1 Abbreviations for 14 industrial sectors

Abbreviation	
AGR TRANS	Agriculture
COAL	Coal mining
OILGAS	Oil and gas mining
MINE	All mining industries Except coal, oil, and gas mining
LIGHT ELE,GAS,WATER,CONS,TER	Light (labor-intensive) Manufacturing industries
HEAVY	Energy-intensive industries such as coke and steel industries
CAPTIAL	Capital-intensive industries
TECH	Technology-intensive industries
ELE	Electricity industry
GAS	Gas supply
WATER	Water supply
CONS	Construction
TER	Tertiary industry
TRANS	Transportation

$$\mathrm{QQ}_c = a_c^m\left(\delta_c^m \mathrm{QM}_c^{\rho_c^m} + \delta_c^{dm} \mathrm{QD}_c^{\rho_c^m}\right)^{1/\rho_c^m}, \tag{3}$$

$$\mathrm{QEX}_c = \left(\frac{\delta_c^{\mathrm{dex}}}{\delta_c^{\mathrm{ex}}} \times \frac{\mathrm{PEX}_c}{\mathrm{PD}_c}\right)^{\sigma_c^{ex}} \mathrm{QD}_c, \tag{4}$$

$$\mathrm{QX}_c = a_c^{\mathrm{ex}}\left(\delta_c^{\mathrm{ex}} \mathrm{QEX}_c^{\rho_c \mathrm{ex}} + \delta_c^{\mathrm{de}} \mathrm{QD}_c^{\rho_c \mathrm{ex}}\right)^{1/\rho_c^m}, \tag{5}$$

where QM, QD, QQ, and QEX represent the quantity of imported, domestic sales, domestic consumption, and exported commodity c. all δ, a and σ are parameters for the Constant Elasticity of Transformation (CET) function based on the Armington assumption.[1] It should be noted that Eqs. (2)–(5) are also applied for domestic trade, including electricity transmission. Hence, there is a market competition between local power and transmitted power. The prices of imported and domestic trade goods are kept constant from 2017 to 2050 in our research.

Income and expenditure blocks

Household and government expenditure is determined by consumption propensity:

$$\mathrm{QH}_c = \mathrm{alpha}_c \mathrm{YH}(1 - \mathrm{htax})(1 - \mathrm{MPSH})/\mathrm{PQ}_c, \tag{6}$$

[1] $\sigma = 1 - 1/\delta$.

$$\mathrm{YH} = \mathrm{lin} \sum \mathrm{PL}_c \mathrm{QL}_c + k \times \sum \mathrm{QK}_c \mathrm{PK}_c + \mathrm{GtoH}, \tag{7}$$

where QH, YH, hatx, and GtoH represent the consumption and income of households, income tax, and transfer payments from government to households. alpha, MPSH, lin and k are propensity of consuming commodity c, saving rate of household, return rate of labor and capital parameters.

$$\mathrm{QG}_c = \mathrm{beta}_c(\mathrm{YG}(1 - \mathrm{MPSG}) - \mathrm{GtoH})/\mathrm{PQ}_c, \tag{8}$$

$$\mathrm{YG} = \sum \mathrm{tp}_c \mathrm{PX}_c \mathrm{QX}_c + \mathrm{htax} \times \mathrm{YH} + \sum \mathrm{tm}_c \mathrm{PWM}_c \mathrm{QM}_c \mathrm{EXR}, \tag{9}$$

where QG and YG represent the consumption and income of government. MPSG, beta, tm, and EXR represent the saving rate, consumption propensity of the government, import tariff, and currency exchange rate. All these data are calibrated using the Shandong Statistical Yearbook.[2]

Mechanism of power market and LBD of RE

The CGE model in this research adopts a LBD mechanism for RE development, including solar and wind power generation and storage. In addition to RE, hydro, nuclear, and thermal power are considered in competition within the power market (Fig. 1). The internal competition in the power market is determined by market share and relative mechanisms based on our past research (Shi et al. 2023).

$$\mathrm{RP}_{\mathrm{ren},t} = \mathrm{PXF}_t / \mathrm{PX}_{\mathrm{ren},t}, \tag{10}$$

$$\mathrm{MS}_{\mathrm{ren},t+1} = \mathrm{MS}_{\mathrm{ren},t} + \left(\mathrm{s}_{\mathrm{ren}} - \mathrm{MS}_{\mathrm{ren},t}\right)\left(\mathrm{RP}_{\mathrm{ren},t+1} - \mathrm{RP}_{\mathrm{ren},t}\right), \tag{11}$$

$$\mathrm{MSF}_{\mathrm{thermal},t} = 1 - \sum_{\mathrm{ren}} \mathrm{MS}_{\mathrm{ren},t}, \tag{12}$$

$$\mathrm{REN} = \{\ \mathrm{Wind},\ \mathrm{Solar}\} \text{ and } \mathrm{ren} \in \mathrm{REN}.$$

As shown in Eq. (10), the relative prices $\mathrm{RP}_{\mathrm{ren},t}$ refer to dividing the thermal power price PXF_t by RE prices $\mathrm{PX}_{\mathrm{ren},t}$. The demand or market share of RE $\mathrm{MS}_{\mathrm{ren},t}$ will increase when relative prices of RE is higher (i.e., the price of RE is decreasing compared to thermal power). Equation (11) indicates this mechanism at an annual unit level. s_{ren} is a parameter deciding the upper bound of market share, i.e., solar and wind power are set at 80% in this study. Equation (12) calculates the market share of thermal power.

Furthermore, this study adopts LBD for solar and wind power:

$$\mathrm{AVC}_{\mathrm{ren},t} = \mathrm{lb}_{\mathrm{ren}} \mathrm{KS}_{\mathrm{ren},t}^{-\mathrm{lx}_{\mathrm{ren}}}, \tag{13}$$

$$\mathrm{KS}_{\mathrm{ren},t} = \mathrm{KS}_{\mathrm{ren},t-1}\left(1 - \delta_{\mathrm{ren}}\right) + \mathrm{e}_{\mathrm{ren},t}. \tag{14}$$

As shown in Eqs. (13) and (14), the average cost of wind and solar power $\mathrm{AVC}_{\mathrm{ren,t}}$ is a decreasing function of knowledge stock $\mathrm{KS}_{\mathrm{ren},t}$ which is accumulated through power generation $e_{\mathrm{ren},t}$ with an annual depreciation δ_{ren}.[3] The learning rates for solar and wind power improvements $-\mathrm{lx}_{\mathrm{ren}}$ are set at 0.08 and 0.1, respectively, based on Zhu et al. (2015). The $\mathrm{lb}_{\mathrm{ren}}$ is calibrated using historical data. In addition, the demand for storage of wind and solar power is derived from Dai et al. (2017), and is also applied to the LBD mechanism in Eqs. (13) and (14), where the knowledge stock is determined by storage power, and the learning rate is based on Guo and Fan (2017).

The investment in RE is provided by the official website of the 14th Five-Year Plan.[4] However, the detailed plan after 2025 assumes a decreasing annual investment growth rate of 1.5–2%, 3–5%, and 5–7% for hydro, nuclear, and RE from 2025 to 2050, respectively.

GAINS model

The GAINS model is extensively utilized to evaluate air quality, pollutant emissions, and health impacts. It encompasses grid-specific particulate matter ($PM_{2.5}$) transfer coefficients and population distribution (Kiesewetter et al. 2015; Qin et al. 2017). The model simulates the reactions of $PM_{2.5}$ concentrations to changes in primary $PM_{2.5}$ emissions and secondary inorganic aerosols generated from emissions of SO_2, NO_X, and NH_3. These processes are modeled using the global-regional chemical transport model EMEP (European Monitoring and Evaluation Program), which is embedded within the GAINS model (Amann et al. 2011; Aman et al. 2008). The EMEP Chemistry Transport Model was run at a $0.5° \times 0.5°$ resolution for the full meteorological year 2015, with additional reduction simulations for city low-level sources conducted at a finer $1° \times 1°$ resolution. By integrating the EMEP model, the GAINS model can obtain $PM_{2.5}$ concentration data at a $1° \times 1°$ resolution, which can then be aggregated to derive $PM_{2.5}$ concentrations at the city and provincial levels.

In the GAINS model, historical emissions of air pollutants and greenhouse gases (GHGs) are estimated for each country. This estimation process relies on data

[2] http://tjj.shandong.gov.cn/tjnj/nj2018/zk/indexch.htm.

[3] Initial knowledge stock derives from summation of historical power generation at 5% annual depreciation.

[4] http://nyj.shandong.gov.cn/art/2023/3/8/art_100399_10296693.html

collected from international emission inventories as well as national information provided by individual countries. Emission projections from the GAINS model span from the present to the year 2050, with projections specified at 5-year intervals.

Emission estimates

In this study, we use the GAINS-China model, which applies province-level data inputs for China. For each pollutant, GAINS-China estimates emissions by considering activity data, uncontrolled emission factors, the effectiveness of emission control measures in removing pollutants, and the degree of implementation of these measures:

$$E_{i,p} = \sum_{k} \sum_{m} A_{i,k} ef_{i,k,m,p} x_{i,k,m,p}, \tag{15}$$

where i, k, m, p represent province, activity type, abatement measure, and pollutant, respectively. $E_{i,p}$ are emissions of pollutant p (for SO_2, NO_x, NH_3, $PM_{2.5}$, CO_2, CH_4, N_2O, etc.) in province i. $A_{i,k}$ is activity level of type k (e.g., coal consumption in power plants) in province i. $ef_{i,k,m,p}$ is emission factor of pollutant p for activity k in province i after application of control measure m. $x_{i,k,m,p}$ is share of total activity of type k in province i to which a control measure m for pollutant p is applied. In the GAINS-China model, future emissions are estimated using Eq. (1), which adjusts activity levels based on the results of the CGE model. Though the CGE model provides provincial results, the GAINS-China model outputs data at a grid scale, which is further processed to derive city-level $PM_{2.5}$ concentrations and mortality rates for more accurate human health capital estimation.

Modeling the interplay of precursor emissions on $PM_{2.5}$ levels

The health impact assessment in GAINS is based on epidemiologic studies linking premature mortality to annual mean concentrations of $PM_{2.5}$ monitored at urban background stations. The source-receptor relationships developed for GAINS describe the response in annual mean $PM_{2.5}$ levels to changes in precursor emissions such as SO_2, NO_x, NH_3, and primary $PM_{2.5}$ within a limited range around a reference emission level. The following equation represents particulate matter derived from anthropogenic primary PM emissions and the formation of secondary inorganic aerosols:

$$\mathrm{PM}_j = \sum_i \mathrm{pm}_i \mathrm{PP}^A_{i,j} + \sum_i s_i \mathrm{S}^A_{ij} + \sum_i a_i \mathrm{A}^A_{ij} + \sum_i n_i \mathrm{N}^A_{ij} + k_{0,j}, \tag{16}$$

where PM_j are annual mean concentration of $PM_{2.5}$ at receptor point j,s_i, n_i, a_i, pm_i are emissions of SO_2, NO_x, NH_3 and primary $PM_{2.5}$ in country i, respectively. $A^A{}_{ij}$, $N^A{}_{ij}$, $S^A{}_{ij}$, $PP^A ij$ are matrices with coefficients for reduced (A) and oxidized (N) nitrogen, sulfur (S), and primary $PM_{2.5}$ (PP) for annual calculations. $c0$, $c1$, $c2$, $c3$, $k0$, j, $k1$, j, $k2$, j are model parameters.

This equation does not account for PM from natural sources or primary and secondary organic aerosols due to uncertainties in current modeling capabilities. Therefore, it does not fully replicate the observed mass of $PM_{2.5}$ in ambient air. The results of this approach should thus be compared against observations of the individual species that are modeled.

Consequently, the health impact assessment in GAINS exclusively focuses on changes in specified anthropogenic precursor emissions, without accounting for the largely unknown role of secondary organic aerosols and natural sources.

Estimation of future human capital

According to the framework of this study, we adjust the future sustainability under the IW framework into three components: produced capital, carbon damage, and health capital (Fig. 1). The sustainability value is the sum of these three components. Produced capital arises from the net investment in fixed assets, accounting for depreciation, and contributes to human capital, natural capital, and produced capital. The damage caused by carbon emissions is treated as an adjustment in sustainability under IW framework, and this study focuses on estimating health capital as part of human capital (Arrow et al. 2012; Managi and Kumar 2018). Health capital serves as a proxy for human capital, focusing on the changes in and impacts on life expectancy among populations under different pollution levels.

Health capital is calculated as the sum of the value V for an individual of age a surviving to age T as shown below:

$$V(a) = \frac{h\left(1 - \mathrm{e}^{-\delta(T-a)}\right)}{\delta}, \tag{17}$$

$$h = \mathrm{VSL} / \left[\sum_{a=0}^{100} \pi(a) \left(\sum_{T=0}^{100} f(T|T \geq a) \left(\sum_{t=0}^{T-a} 0.95^t \right) \right) \right], \tag{18}$$

$$f(T|T \geq a) = 1 - \lambda \mathrm{e}^{-\lambda(T-a)}, \tag{19}$$

$$H(a) = \int_a^{\infty} V(a,T) f(T|T \geq a) \mathrm{d}T, \tag{20}$$

where h, δ, VSL $\pi(a)$ and $H(a)$ represent additional years of life (VSLY), the time discount rate, the value of a statistical life (VSL), the proportion of people of age a, and health

Table 2 Parameters design

AEEI	Li et al. (2017)
lx	Solar and wind power generation (Zhu et al. 2015)
	Solar and wind power storage (Guo and Fan 2017)
T	Survival age is 100
λ	Mortality rate is given by National Bureau of Statistics (2021)
s_{ren}	Hydro, nuclear, wind and solar are 0.2,0.4,0.8 and 0.8, respectively
δ *and a*	All calibrated by CES function based on historical data
lb	Calibrated by Eq. (13) based on historical data

capital, respectively. VSL is roughly estimated by past studies, age structure, and GDP data from Beijing, China, at \$1.58 million (Viscusi and Aldy 2003; Jin and Zhang 2018; Jin et al. 2020). The value of 0.95 in Eq. (18) represents the annual depreciation of 5% in the value of future years of life. Equation (19) calculates the conditional probability density of death at age *T*, given survival to age a, where λ indicates the constant mortality hazard rate over a 5-year period. This rate is influenced by $PM_{2.5}$ levels over time and carbon pricing in this study (Arrow et al. 2012). Based on previous calculations, Eq. (20) provides the method to obtain the value of health capital for an individual of age *a*.

Due to climate change caused by increasing fossil fuel consumption, rising carbon emissions have a damaging effect on human capital (Asghar et al. 2020). In addition, the relationship between carbon emissions and mortality has been emphasized in previous studies (Ibrahim 2022; Adeleye et al. 2023).Therefore, this research adopts a linear relationship between changes in $PM_{2.5}$ concentration and mortality, based on Pope III et al. (2002)[5] that is caused by carbon abatement policy and the all-cause mortality data are calculated at city-level in GAINS model. By obtaining different $PM_{2.5}$ concentrations under different scenarios, we calculate the resulting mortality rates, which are then used with VSLY and population cohorts at different ages to estimate health capital.

Scenarios for model

In this study, we set up two scenarios: a business-as-usual (BaU) scenario and a carbon tax scenario. To evaluate the impacts of environmental policy on future sustainability, this research conducts a carbon tax analysis for comparison with BaU. Table 2 shows the parameter settings, where AEEI refers to autonomous energy efficiency improvement. The CGE model runs scenarios and provides feedback to the GAINS model regarding changes in $PM_{2.5}$ concentrations, which also affects health capital. The only difference between the two scenarios is the implementation of the carbon tax, with all other parameters (including TFP) remaining the same.

Table 3 TFP and GDP growth

	2020–2030 (%)	2031–2040 (%)	2041–2050 (%)
GDP	4.84	2.68	1.19
TFP	2.69	2.66	1.68

BaU scenario of CGE model

The GDP and population growth rates are estimated based on past studies, the Shandong Statistical Yearbook, and the China Statistical Yearbook of Population Census (Yuan et al. 2020; Cao et al. 2021; National Bureau of Statistics 2021). Table 3 shows the TFP growth rate from 2020 to 2050, calibrated by GDP growth rates.

Carbon tax scenario (CT) of CGE model

Shi et al. (2023) shows the offset effect of improved RE on GDP loss caused by a carbon tax in the long term. However, economic impact does not equate to wealth, and it is necessary to investigate whether carbon pricing also contributes positively to future sustainability. Figure 3 shows the carbon tax in this research, following Cao et al. (2021).

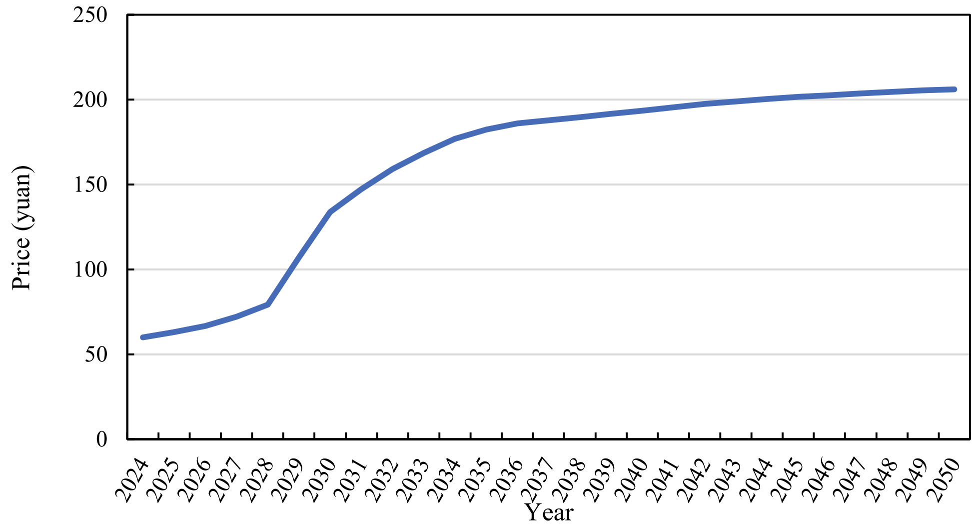
Data on RE development

This study discusses the health risks associated with reducing thermal power and its impact on LBD in RE in Shandong province, China. Shandong has the largest thermal power generation in China's provincial electricity market, with non-thermal power generation accounting for only 5% of total generation in 2017, excluding power imported from other provinces (Shandong Provincial Bureau of Statistics 2018). In response, the Shandong government has decided to develop RE and reduce thermal power generation to achieve carbon peak by 2030.[6] By 2022, the ratio of non-thermal

[5] The Relative risk equals to 0.006 × PM2.5 concentration + 1. Moreover, only people whose age over 30 will be affected by it.

[6] www.shandong.gov.cn/art/2023/1/1/art_97904_569558.html

Fig. 3 Carbon tax (Yuan/ton)



power in Shandong had risen to over 16%. To further enhance RE locally, the Shandong government released guideline for energy storage by 2025, aiming to increase storage installation to 5-million kw.[7] The energy storage in Shandong primarily supports RE, including electrochemical, compressed air, hydrogen, and electric vehicles. Thus, the learning rate for LBD in energy storage in Shandong is set at 0.7, based on Guo and Fan (2017).

Results

In this section, we compare the results between the BaU scenario and the scenario with a carbon tax (CT).

Non-fossil fuel consumption

The BaU results are based on the data and TFP growth rates shown in Table 2. Figure 4 illustrates the ratio of non-fossil fuel consumption to total primary energy consumption (Ps) in both scenarios. Comparing the growth rates of Ps between 2025–2030 and 2040–2050, the impact of LBD on RE development is significantly more pronounced in the long term, as coal-fired power begins to exit from 2035 with 550 Tera-watt hour (Twh). Non-fossil energy grows faster in the carbon tax scenario than in the BaU scenario. The carbon tax significantly reduces thermal power generation in 2050, with a reduction of 76% compared to BaU. However, hydro, nuclear, wind, and solar power increase by only 2.8%, 5.1%, 1.7%, and 6.7%, respectively, in 2050. This suggests that the reduction in the non-fossil fuel energy consumption ratio is primarily due to the contribution of domestic imported power rather than the development of RE, as total power generation is reduced by 23% in 2050.

GDP, carbon emission, and carbon intensity

Table 4 demonstrates the carbon emission, GDP, and carbon intensity for both BaU and CT scenarios. The GDP of scenario CT is always higher than that of BaU, where the change rate of CT compared to BaU ranges from 0.28 to 0.68%. Simultaneously, CO_2 emissions in the CT scenario show a significant reduction, with percentages ranging from − 4.09% in 2025 to − 25.10% in 2050. Interestingly, the carbon tax has a positive but slight impact on GDP and carbon abatement in the initial stage. The carbon peak in the CT scenario is reached in 2027, which is 9 years earlier than in the BaU scenario.

In 2025, the carbon intensity in the BaU scenario is 0.8655, while in the CT scenario, it decreases to 0.8279, representing a reduction of 4.55%. By 2030, the carbon intensity in the CT scenario further decreases to 0.6565, compared to 0.7271 in the BaU scenario, indicating a reduction of 10.74%. This trend continues, with carbon intensity steadily declining in subsequent years under the CT scenario. By 2050, the carbon intensity in the CT scenario reaches 0.2962, reflecting a significant reduction of 34.17% compared to the BaU scenario. According to the World Bank, the global carbon intensity data for 2020 serves as a reference.

Industry structural transition

To illustrate the impact of the carbon tax on industries, we decomposed and integrated the existing industries into 14 sectors. The abbreviations and descriptions of these sectors

[7] nyj.shandong.gov.cn/art/2022/12/30/art_100396_10295574.html.

are listed in Table 1. Figure 3 shows the change rate of value-added in the CT scenario compared to BaU across the 14 sectors.

The carbon tax has a slight impact on the construction, light manufacturing, capital-intensive, oil and gas mining, and water supply industries. However, the effect on energy-intensive industries is also minimal, with the value-added of cement, glass, and ceramic industries increasing. The value-added is calculated by the difference between total output and intermediates. Despite a slight negative impact on these energy-intensive industries, the overall effect leads to GDP growth (Table 4).

The power industry is the most affected sector, as thermal power is the largest consumer of coal and CO_2 emitter in Shandong province. From 2024 to 2028, the negative impact of the carbon tax on thermal power diminishes as RE can meet the initial demand for thermal power. In addition, while the energy cost increase due to the carbon tax is not substantial until 2028, the growing carbon tax eventually leads to the significant exit of thermal power between 2029 and 2031. After 2032, there is a sharp increase in RE investments, contributing to economic growth.

Not surprisingly, investments from energy-intensive industries flow into the relatively cleaner tertiary sector. Despite significant investment in the tertiary industry, the decreased investment in other industries cannot support rapid development across the entire period, as the growth rate of value-added in the tertiary industry slows after 2033.

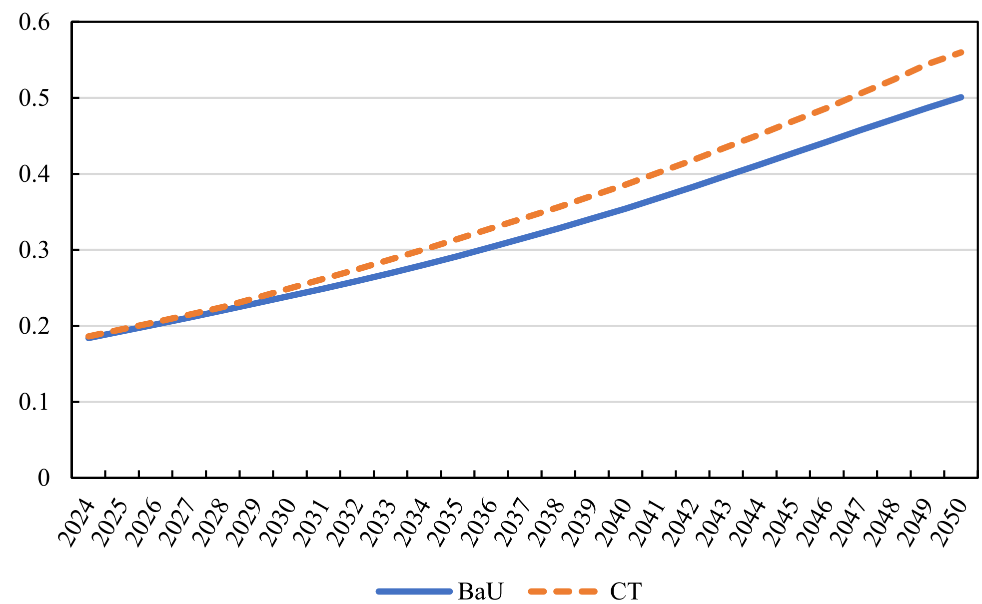


Fig. 4 Ratio of non-fossil fuel consumption to total primary energy consumption

Table 4 Results of GDP, carbon emission, and carbon intensity in CT compared to BaU

	2025	2030	2035	2040	2045	2050
GDP (Billion yuan)						
BaU	11.54	14.08	16.73	19.02	20.69	21.83
CT	11.58	14.16	16.84	19.15	20.82	21.94
Change rate	0.28%	0.52%	0.68%	0.66%	0.60%	0.50%
CO_2 (Billion ton)						
BaU	1.00	1.02	1.08	1.06	0.98	0.87
CT	0.96	0.93	0.92	0.88	0.79	0.65
Change rate	− 4.09%	− 9.23%	− 14.82%	− 16.92%	− 19.94%	− 25.1%
Carbon intensity Ton/1000 yuan						
BaU	0.8655	0.7271	0.6430	0.5595	0.4755	0.3974
CT	0.8279	0.6565	0.5440	0.4618	0.3784	0.2962
Change rate	− 4.55%	− 10.74%	− 18.2%	− 21.2%	− 25.7%	− 34.2%

Health, produced capital, and carbon damage for sustainability

Based on the results derived from the CGE and GAINS models, Table 5 shows the city-level $PM_{2.5}$ concentration change caused by the carbon tax, and Table 6 includes health capital, produced capital, and carbon damage in the long-term future.

We observe that the $PM_{2.5}$ concentration is reduced by the carbon tax policy by around 0.1–1.3 μg/m^3 (less than 5%) as fossil fuel consumption decreases. As a result, the calculation of health capital shows negligible change compared to $PM_{2.5}$ concentration, which will be further discussed in "Health, produced capital, and carbon damage for Sustainability under the IW framework".

As mentioned in Eqs. (12)–(15), the difference between BaU and CT is driven by changes in all-cause mortality rates due to $PM_{2.5}$. The carbon tax significantly reduces carbon emissions, which in turn decreases $PM_{2.5}$ concentrations in each city of Shandong province. Health capital is calculated using VSLY and discounted expected years of life. Although $PM_{2.5}$ has a confirmed impact on health capital, the change in the value of health capital remains considerably smaller than the changes observed in produced capital and carbon damage (Table 6).

The predication of produced capital is entirely provided by the CGE model, derived from net investment in fixed capital with a constant 5% annual depreciation (Managi and Kumar 2018). The carbon tax leads to higher produced capital across all time periods starting from 2025, with the difference increasing until 2040.

Carbon damage is treated as an adjustment for IW estimation, as the negative externalities caused by carbon emissions are not included in natural or health capital. Therefore, carbon damage is considered an exogenous impact on social well-being (Managi and Kumar 2018). Carbon emissions are collected from all local fossil fuel combustion, including industries and households (government). The damage per ton of carbon emission is $50, and carbon damage is calculated by multiplying carbon emissions by the price per unit ton (Tol 2009). Table 5 demonstrates the significant impact of the carbon tax in alleviating carbon damage, with the gap widening as the carbon tax increases.

Discussion

The impact of carbon tax on RE and fossil fuel consumption

Table 4 shows that the BaU results are consistent with Sun et al. (2022), where low-carbon technologies in BaU improve RE and gradually replace coal-fired power, leading to significantly lower coal-fired power demand compared to past studies (Zhang et al. 2023a). Carbon tax policies promote the substitution of cleaner products for dirtier ones through endogenous technological innovation (Acemoglu et al. 2012). In Table 4, carbon emissions decrease at an increasing rate over the long term due to the LBD effect of RE. This effect operates on both sides: the exit of thermal power prompted by the carbon tax creates a market for RE, accelerating technological improvements, with the effect becoming stronger as higher carbon taxes are implemented. The greater the exit caused by higher carbon taxes, the more market space is created for RE, encouraging technological improvements over time. As a result, the significant exit of thermal power and fossil fuel consumption directly contributes to the reduction of carbon damage. However, it is important to note that the reduction in thermal power is largely driven by an increased share of imported electricity rather than locally generated RE power.

Under the BaU scenario, Shandong Province is projected to reach the global average level of carbon intensity by 2040. In contrast, under the CT scenario, Shandong is expected to achieve this level five years earlier, by 2035. Furthermore, by 2050, the CT scenario is forecasted to reach the carbon intensity level of high-income countries. The two-tailed t test shows no significant difference in the economic growth rate between the two scenarios ($p = 0.50$), but the decline in carbon intensity in the CT scenario is significantly higher than in the BaU scenario ($p = 0.003$). This suggests that the carbon tax does not impact the economic growth rate but accelerates the decline in carbon intensity.

The next section will focus on discussing the positive impacts of the carbon tax on both economic growth and carbon abatement, specifically in Shandong province. This involves examining the specific context and dynamics of Shandong's economy and energy sector to better understand how the carbon tax contributes to these positive outcomes within that regional context.

Impact of industry structural transition on GDP

The cement, glass, and ceramic industries account for 2.75%, 0.3%, and 0.16% of the total value-added in energy-intensive industries, indicating that technological and energy efficiency improvements are possible at a small scale (Li et al. 2023). In contrast, the petroleum refining, chemical, and rubber industries account for 11%, 38%, and 17%, respectively. The negative impact of the carbon tax on these industries leads to a decrease in the overall value-added of energy-intensive industries.

In Fig. 5, the carbon tax sharply increases from 2029 to ensure carbon peak by 2030, significantly affecting the

Table 5 $PM_{2.5}$ concentration of 13 cities under BaU and CT scenarios by 2050 (unit: μg/m^3)

Cities	Scenarios	2025	2030	2035	2040	2045	2050
Jinan	BaU	43.57	40.70	39.44	37.90	37.17	36.27
	CT	43.39	40.14	38.46	36.84	36.02	34.99
Qingdao	BaU	34.57	32.38	31.50	30.41	29.98	29.44
	CT	34.45	32.03	30.89	29.75	29.26	28.64
Zibo	BaU	40.48	37.92	36.76	35.28	34.58	33.69
	CT	40.29	37.34	35.76	34.19	33.39	32.39
Zaozhuang	BaU	45.28	42.60	41.32	40.01	39.41	38.61
	CT	45.15	42.21	40.65	39.28	38.61	37.73
Dongying	BaU	35.69	33.68	32.79	31.69	31.20	30.56
	CT	35.55	33.27	32.09	30.92	30.37	29.65
Yantai	BaU	28.61	26.96	26.30	25.47	25.15	24.74
	CT	28.52	26.69	25.82	24.96	24.59	24.12
Weifang	BaU	37.12	34.70	33.69	32.43	31.86	31.13
	CT	36.96	34.24	32.90	31.56	30.92	30.10
Jining	BaU	49.01	45.94	44.51	42.99	42.28	41.37
	CT	48.85	45.46	43.67	42.08	41.29	40.28
Tai'an	BaU	44.53	41.58	40.31	38.84	38.15	37.27
	CT	44.35	41.07	39.42	37.86	37.09	36.11
Weihai	BaU	25.12	23.77	23.18	22.50	22.25	21.91
	CT	25.05	23.56	22.81	22.09	21.80	21.42
Rizhao	BaU	35.38	33.14	32.22	31.18	30.75	30.18
	CT	35.26	32.80	31.64	30.54	30.06	29.42
Linyi	BaU	39.39	36.88	35.81	34.65	34.15	33.48
	CT	39.26	36.52	35.19	33.97	33.41	32.67
Dezhou	BaU	47.50	44.38	42.92	41.35	40.64	39.77
	CT	47.33	43.88	42.07	40.41	39.62	38.66
Liaocheng	BaU	51.21	47.90	46.31	44.70	43.99	43.14
	CT	51.05	47.44	45.51	43.83	43.05	42.11
Binzhou	BaU	41.11	38.50	37.32	35.90	35.25	34.44
	CT	40.94	37.99	36.43	34.93	34.20	33.28
Heze	BaU	52.80	49.63	48.07	46.65	46.03	45.27
	CT	52.68	49.30	47.49	46.02	45.34	44.52

electricity industry. The exit of thermal power outweighs the entry of RE because the LBD effect is not a short-term mechanism. The turning point occurs in 2032, as RE becomes more competitive and replaces thermal power. As the carbon tax increases, the negative impact on the power industry continues to rise by 2050, with a carbon tax of 206 Yuan/ton likely acting as a threshold for thermal power plants.

Although there is significant decrease in value-added in the power industry, the growth of the tertiary industry leads to an overall increase in value-added, as the power industry accounts for only 10% of the total value-added in Shandong's tertiary sector. By comparing the transportation, energy-intensive, and electricity industries with the tertiary sector, Fig. 5 reveals a significant structural shift from energy-intensive industries to a lower-carbon industrial structure, driven by sensitivity to energy cost increases caused by the carbon tax. As a result, the entry of the tertiary industry roughly exceeds the exit of other industries, indicating that the low-carbon shift is a solution to the dilemma between environmental sustainability and economic growth in energy-consuming areas (Zhang and Liu 2022).

Moreover, the industrial transition contributes most of the carbon abatement, suggesting that the carbon tax has only

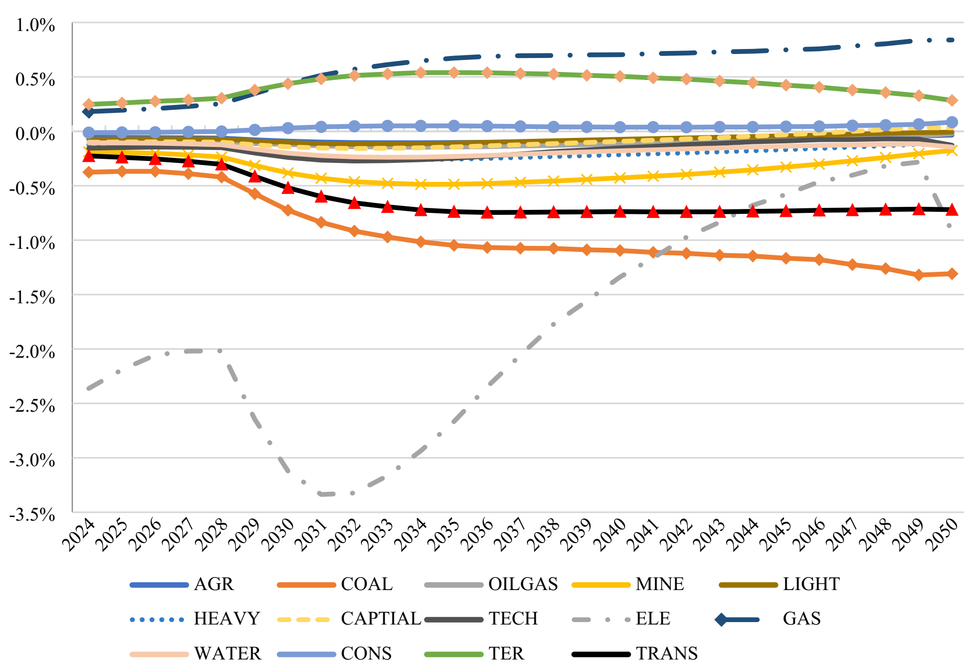
Table 6 Health and produced capital, carbon damage, and differences between CT and BaU

Unit: million $	2025	2030	2035	2040	2045	2050
Health capital						
BaU	11,025,817.58	11,025,837.56	11,025,846.48	11,025,856.53	11,025,861.00	11,025,866.67
CT	11,025,818.70	11,025,840.86	11,025,852.20	11,025,862.79	11,025,867.78	11,025,874.11
Difference	1.11	3.31	5.72	6.26	6.78	7.45
Produced capital						
BaU	626,257	640,976	673,318	671,569	631,532	570,961
CT	626,387	641,585	674,288	672,602	632,554	571,896
Difference	130	609	970	1033	1022	935
Carbon damage						
BaU	− 49,957	− 51,203	− 53,784	− 53,207	− 49,193	-43,385
CT	− 47,915	− 46,475	− 45,811	− 44,203	− 39,383	-32,497
Difference	2042	4728	7973	9004	9810	10,888
Total						
Difference	2184	5351	8960	10,061	10,854	11,845

The unit of all capital and damage is prices in in 2000 US$. Value change equals to the value from CT minus the value from BaU. Total refers to the summation of CT-BaU of health capital, produced capital and carbon damage

a slight impact on the power market, as the power generation structure hardly changes under the carbon tax by 2050. Similarly, the demand for imported electricity increases only slightly to meet economic growth needs. In other words, the carbon tax primarily alters the industrial structure, with the reduction of fossil fuels largely driven by the exit of energy-intensive industries, excluding thermal power. At the same time, the growth of the tertiary industry increases electricity demand, which helps maintain thermal power generation, as the limited development of RE storage restricts further growth. This necessitates additional environmental policies, such as subsidies and electrification, to promote RE development. The lack of direct support for RE leads to increased reliance on imported electricity to alleviate carbon abatement pressure. As a result, the structural transition induced by the carbon tax has minimal effect on local power supply and demand, indicating stable economic growth without significant risks.

Fig. 5 Change rate of value-added of CT compared to BaU



Health, produced capital, and carbon damage for Sustainability under the IW framework

Although co-benefits between carbon abatement and air pollution reduction exist, a single carbon pricing method is insufficient to have a substantial long-term impact on improving health capital. While the significant effect of low-carbon policies on air pollution reduction can yield considerable monetary gains from reduced medical expenditures, it does not directly translate into health capital gains (Lin et al. 2023). Although carbon emission taxation can encourage power transmission, clean technology adoption, and energy efficiency improvements, the reduction in fossil fuel consumption is not enough to significantly affect health capital through air pollution reduction (Mier et al. 2024). As discussed in "Impact of industry structural transition on GDP", a single carbon tax has minimal effect on improving the fossil fuel-based power structure in Shandong Province, with most regional $PM_{2.5}$ concentrations in the CT scenario failing to meet the current Chinese standard of 30 μg/m^3. Furthermore, the calculation of health capital based on mortality may not be fully affected by air pollution if there is no long-term exposure to ambient pollution (Shan et al. 2020). In addition, the rough relationship between mortality and $PM_{2.5}$ may weaken the carbon tax's impact on health capital. Meanwhile, since the VSL is assumed exogenously in this research, changes in health capital are solely determined by changes in mortality rates caused by air pollution. Therefore, the impact of the carbon tax may be further distorted.

Regarding produced capital, as discussed earlier, the carbon tax facilitates a shift in investment patterns from energy-intensive to technology-intensive industries (Jin et al. 2024). The disinvestment in carbon-intensive industries and investment in low-carbon industries leads to an increase in produced capital, as the tertiary industry offers higher returns. In other words, carbon pricing internalizes the social cost associated with carbon emissions, making clean capital more attractive to investors.

Overall, the carbon tax has a positive impact on future sustainability, as the sum of health, produced capital, and carbon damage remains positive, with higher carbon taxes leading to greater sustainability in the long term. There is no doubt that carbon pricing is beneficial for achieving future sustainability goals. However, over 90% of the change in sustainability under the IW framework is attributed to the reduction of carbon damage or, in other words, direct carbon abatement. The reduction in carbon emissions induced by the carbon tax is not significant enough to improve health and produced capital. In addition, we find that health and produced capital show less improvement after 2040. While health capital experiences a rebound due to improved RE, the shift in produced capital from dirty to clean industries slows down due to the marginal effect of the carbon tax.

Conclusions

In summary, due to the lack of comprehensive evaluation of future sustainability, this research establishes an IW-related framework to analyze future sustainability. This framework combines a numerical framework for economic and policy evaluation with an assessment of the impacts on human health through future potential and costs for air pollution reduction, referring to the CGE and GAINS models, respectively. The CGE model simulates the economy under a carbon tax at the provincial level, quantifying the impacts of the carbon tax on economic growth, with a clear focus on produced capital. Meanwhile, the GAINS model uses the CGE model output to derive air pollution levels in two scenarios, providing mortality rates for health capital estimation, and subsequently calculating human capital and carbon damage. By combining these two models, this study introduces a method to estimate future sustainability, dividing it into health capital, produced capital, and carbon damage.

Our results show that the carbon tax, with the endogenous improvement of RE, is conducive to achieving more overall environmental and economic benefits. This shift stems from the transition to a low-carbon industrial structure, though its impact is less significant than the increased reliance on transmitted electricity. Regions tend to rely more on domestic imported electricity, as this reduces local carbon emissions and its negative impact on sustainability within the IW framework when no policy such as subsidy directly encouraging RE development. The shift in investment patterns from heavy manufacturing to the tertiary industry indicates that clean capital flows play a key role in GDP growth under the carbon tax. In addition, the carbon tax significantly reduces air pollution and carbon emissions, bringing co-benefits. The reduction in $PM_{2.5}$ concentrations at the city level increases individuals' remaining life expectancy, improving health capital and reducing carbon damage. While the impact of the carbon tax on health capital is modest, this study provides a method to estimate future sustainability, including policy evaluation, which is crucial for assessing SDG challenges in future.

However, this study has several limitations. First, it lacks a detailed investigation into the relationship between air pollution and mortality. Although the $PM_{2.5}$ concentration simulated by the GAINS model is detailed to a $1° \times 1°$ resolution, the matched population health conditions are only available at the city level. In addition, the exposure-risk relationship utilized in this study does not comprehensively capture the health impacts of air pollution improvements. Furthermore, the Chinese regional VSL used in health capital estimation has been updated by recent studies, but the data varies in magnitude, and provincial data could offer more reliability. The VSL is assumed exogenously in this study, meaning that changes in health capital are solely driven by mortality rate changes resulting from air pollution. Therefore, the impact of the carbon tax may be further distorted. Finally, the future sustainability estimation presented here is preliminary, as it excludes natural capital components such as timber, fisheries, and fossil fuel extraction. Moreover, the estimation of RE in our index should be considered in future research, as the LBD effect is crucial in the power market, leading to significant increases in non-fossil fuel consumption. In addition, the single-region CGE model used in this study cannot capture spillover effects, such as interregional dependencies and national-level impacts. For example, interregional dependencies might alter the power structure through domestic electricity imports, potentially leading to a sharp reduction in $PM_{2.5}$ concentrations due to the exit of thermal power plants. Therefore, further research should focus on capturing interregional linkages and their impact on multi-regional air pollution and health capital using a multi-regional CGE model.

Appendix

See Table 7.

Table 7 Population of age ranging from 30 to 100 at city-level in 2020 and 2050

City	Population (2020)	Population (2050)
Jinan	6,069,260	6,483,381
Qingdao	6,912,790	7,029,865
Zibo	3,335,436	3,134,337
Zaozhuang	2,438,588	2,763,711
Dongying	1,522,724	1,520,650
Yantai	5,275,749	4,577,811
Weifang	6,466,727	6,392,774
Jining	5,547,063	5,879,879
Taian	3,806,459	3,721,973
Weihai	2,210,553	1,841,072
Rizhao	2,018,503	1,841,072
Linyi	7,018,432	7,824,534
Dezhou	3,770,771	3,901,006
Liaocheng	3,822,156	4,256,933
Binzhou	2,704,984	2,686,986
Heze	5,374,693	6,327,027

0–29 data are not listed but it is used to predict future population data by using birth rate and death rate in BaU

Author contributions BS: Conceptualization, Methodology (CGE), resources, software, formal analysis, writing—original draft, writing—review and editing. QJ: Methodology (GAINS), resources, software, formal analysis, model validation, writing—original draft, Writing—review and editing. MS: conceptualization, model validation, Writing—review and editing. SM: project administration, supervision.

Data availability The data is available on the request.

Declarations

Conflict of interest The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: 'Professor Shunsuke Managi' on this paper is a guest editor, he was blinded during the review process and the paper was handled by another editor.

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