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LETTER

How to balance China's sustainable development goals through industrial restructuring: a multi-regional input–output optimization of the employment–energy–water–emissions nexus

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Abstract

To effectively manage economic transition and pursue sustainable development, the Chinese government has promulgated a series of policies in the 13th Five Year (2016–2020) Plan (FYP), covering social security, economic growth, energy transition, resource conservation, and environmental protection. To balance the various 13th FYP policy targets, we propose a multi-objective optimization model based on multi-regional input–output analysis. The model integrates the management of employment, energy consumption, water use, carbon emissions, and pollutant emissions by determining a policy-dominated industrial restructuring pathway that would best achieve consistency in sustainable development policies, adaptation to the national industrial development trend, and regional equity among China's provinces. Synergies and trade-offs among various policies are also discussed. Our optimization results show that an energy-consumption-dominated industrial restructuring pathway is the best solution, as it would satisfy various sustainable targets, facilitate (restrain) development of high-value-added (high-energy-consumption and high-emissions) sectors, as well as improve regional equity. Therefore, to realize sustainability, the energy policy should be prioritized when formulating an industrial restructuring pathway. Applying such a multi-objective optimization model provides policymakers with a comprehensive approach to support sustainable development policies.

1. Introduction

Sustainable development is a key issue when integrating social, economic, energy, resource, and environmental policy considerations. Environmental emission caused by excessive use of fossil fuel is the biggest obstacle in achieving sustainable development. Sustainability generates synergies and requires trade-offs among the nexus of society, economy, energy, resources, and environment. Specifically, economic development leads to an increase in energy and resource consumption as well as environmental emissions; meanwhile, energy conservation and emission reduction policies may hinder economic growth. This is especially true for China, the world's largest energy consumer [1]. Industrialization, accompanied by energy consumption, promotes rapid economic development. Although the Chinese government strives to propel transition to renewable energy, energy consumption is still dominated by fossil fuels, and this partly accounts for carbon emissions related to climate change, air pollutions, and water scarcity [2]. Local unemployment caused by urbanization is also an important factor that hinders economic development [3].

To realize sustainable development and fulfill emission reduction commitments, the Chinese government has promulgated a series of social and environmental policies and set numerous national goals in the 13th Five Year (2015–2020) Plan (FYP), which address maintaining steady economic growth, tackling unemployment, reducing energy consumption, reducing water use, and mitigating emissions. However, a dilemma arises when deciding among conflicting objectives or policy priorities, necessitating trade-offs [4]. Due to these interactions, it has become increasingly prominent for policymakers to settle these goals in different ways [5]. Meanwhile, China's development plans have vital global implications because of the country's enormous economy and population [2]. Additionally, spatial heterogeneity and provincial interdependence in China cause unfair trade-offs [6]. Thus, in keeping with the trend of the nation's industrial development, how to adjust the sectoral production structure of each of China's provinces to balance various conflicting goals and realize regional equity is an essential issue to address.

Solutions regarding sustainable development require an overarching strategy, but they must also be contextualized locally [7]. Interdisciplinary approaches face multiple challenges, such as lack of local knowledge and physical resource constraints [7], shortage of holistic and localized approaches [8], and low levels of communication among various stakeholders [9]. [10] verified that the complex characteristics of interconnecting systems and nonstandard tools are the main factors leading to the lack of unified applications in nexus-issue's decision making. An increasing number of studies on multi-objective connections tend to analyze the interconnection issue from a one-way perspective and quantitatively assess the effects of one objective on others [11]. For instance, [12] evaluated the impacts of energy structure on Shandong province's resources and environment, while [13] estimated the effects of ethanol consumption and international exports on Brazil's land and water footprint. However, these studies either did not provide an explicit solution for a country or a region to meet the divergent targets simultaneously [14] or did not take into account inter-sector coordination and collaboration [15]. Although a few studies focused on optimizing solutions to meet multi-objectives or materials balance principle for coal power plants [16], the electricity sector [17], or thermal power industry [18], they did not take sectoral interdependence into account. A specific sector's production is not isolated and requires collaboration with other sectors. Additionally, the security of a specific sector's production, along with related supply chains, promotes interconnections due to mutual influences [5]. Hence, to achieve multiple conflicting objectives, the overall optimization pathway requires consideration of all sectors and their relationships.

Input–output analysis (IOA) is widely applied for estimating environmental and socioeconomic effects from sector's perspective [19]. It facilitates quantification of the embodied material input and output relations of all industrial sectors. It also captures the entire supply chain, from production to consumption [20, 21]. Several studies have developed linear programming models with IOA to simulate policy scenarios and optimize industrial structures [22]. Using input–output linear programming models, [23] evaluated positive and negative impacts of environmental taxation policy in China, [24] measured energy-economic recovery resilience in China, while [25] explored the production solution of electric-arc-furnace-based crude alloy steel with minimal losses of alloying elements. Furthermore, combining IOA with a multi-objective linear programming (MOLP) model allows us to capture the nature of diverse aspects, which are often conflicting and non-commensurate [26]. Due to these advantages, an increasing number of studies use multi-objective input–output linear programming models to evaluate synergies and trade-offs in the nexus of economy–society–energy [27], economy–energy–environment [28–31], and food–energy–water [32, 33]. However, most related methods developed recently cover only a few aspects of social, economic, energy, resources, and environmental objectives and lack comprehensive consideration of all sustainable elements and their integration.

In this study, a multi-objective optimization model based on multi-regional input–output (MRIO) analysis is proposed using a Chinese MRIO dataset for integrating the sustainable development policy goals of employment, energy consumption, water use, carbon emissions, and other pollutant emissions (three air pollutants and 13 water pollutants). The model is applied to generate an industrial restructuring pathway that satisfies these conflicting goals, the national industrial development trend, as well as regional equity (the best way possible) by searching for a compromise solution for the Chinese economy by 2020. Policy consistency is described as increasing positive impacts (synergies) and decreasing negative impacts (trade-offs) of a specific policy on other sustainable development goals. The national industrial development trend is interpreted as facilitating the development of high-value-added sectors and restraining the development of high-energy-consumption and high-emission sectors. Meanwhile, regional equity is explained as promoting development in developing regions and keeping development in developed regions. Given the interdependence of multi-sectors and the spatial heterogeneity of multiple regions, the key sectors and regions for industrial restructuring are identified. The marginal contributions of this research are (1) reconciling diversified conflicting targets, (2) incorporating complex resource interdependence, (3) quantifying policy interaction, (4) adaptively optimizing management decisions related to prioritized

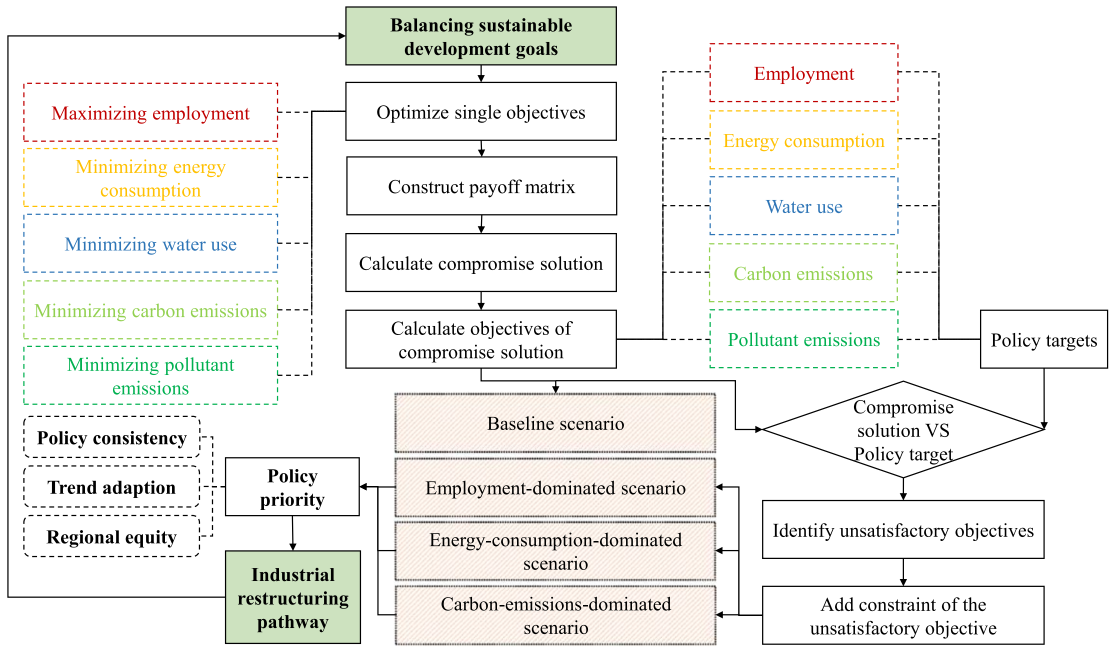


Figure 1. Framework of the multi-objective optimization model based on multi-regional input–output analysis for balancing sustainable development goals.

policies to harmonize multiple policy goals and balance regional development, and (5) analyzing the macro-level issue of multi-dimensional sustainability through a micro-level MRIO optimization model. In addition, the proposed framework is easily reproducible and may serve as a tool for other countries to analyze their sustainable development policies.

2. Method and data

2.1. Framework of the multi-objective optimization model based on multi-regional input–output analysis

A pathway design for policy decisions could be regarded as an MOLP issue, where policymakers need to consider complex objectives regarding the society, economy, energy, resources, and environment. Various algorithms have been proposed to solve MOLP models, such as multi-objective genetic algorithm, multi-objective particle swarm algorithm, multi-objective ant colony algorithm, and differential evolution algorithm [27]. However, either their optimization procedures are like a black box or the weight of each single objective is aggregated subjectively.

Moreover, a pathway design for industrial restructuring should not conflict with the objective of inter-regional and intersectoral interdependence. Thus, based on [34], we propose a multi-objective optimization model based on MRIO analysis for comprehensive and integrated management of the society, economy, energy, resource, and environment. The five dimensions are represented by employment, output, energy consumption, water use, and emissions (carbon emissions and other environmental pollutant emissions), respectively. The model has the advantage of analyzing the macro issues of multi-dimensional sustainable development with a micro model of multi-regional and multi-sectoral input–output optimization.

The flowchart of the solution process for the multi-objective optimization model based on MRIO analysis is illustrated in figure 1. To balance sustainable development goals, we first solve for five single-objective optimizations (see model (1) in supplemental materials): maximizing employment, minimizing energy consumption, minimizing water use, minimizing carbon emissions, and minimizing pollutant emissions. Then, a payoff matrix (see model (2) in supplemental materials) is constructed to evaluate a compromise solution (see model (3) in supplemental materials). Next, the five objectives of the compromise solution are assessed. At this point, the baseline scenario with no constraint of policy target is established based on the results of the previous step. Meanwhile, we compare the five objectives in the baseline scenario with the corresponding policy targets to identify unsatisfactory objectives. In this study, three objectives are identified and the three specific scenarios are formed by adding their policy targets in the constraint (see models (4)–(6) in supplemental materials): employment-dominated scenario, energy-consumption-dominated scenario, and carbon-emission-dominated scenario. By comparing the effects of industrial restructuring in the three scenarios on policy consistency, trend adaptation, and regional equity, a priority policy can be selected and the corresponding industrial restructuring pathway obtained to balance the sustainable development goals. The models of this framework are described in detail in supplemental materials.

2.2. Data

The national and regional input–output tables of China are updated every five years. The latest MRIO table for 30 Chinese provinces and 30 sectors in 2012, excluding Tibet, Taiwan, Hong Kong, and Macao, is acquired from [35]. Data on the number of employed persons and total water use are obtained from the China Statistical Yearbook, while those on total energy consumption are from the China Energy Statistical Yearbook. Data on carbon emissions and other pollutant emissions are from [36, 37], respectively. There are 16 environmental pollutant emissions included in this study, namely, sulfur dioxide (SO_2), nitrogen oxides (NO_x), soot and dust (SD), chemical oxygen demand (COD), ammonia nitrogen (AN), phosphorous, petroleum pollutants, volatile phenol, cyanide, aquatic Hg, aquatic Cd, aquatic Cr, aquatic Pb, aquatic As, aquatic Cu, and aquatic Zn. Data from different sources have diverse sectoral classifications; we adjust them in accordance with the sectoral classification in the MRIO table, which is shown in table S1 is available online at stacks.iop.org/ERL/15/034018/mmedia.

Data for 2020 on employment, energy consumption, water use, carbon emissions, and pollutant emissions are forecasted via the extrapolation of historical trends based on the above-mentioned values. The lower bound (*lb*) and upper bound (*ub*) of the changing rates of total outputs are 0.864 and 1.168, which are determined by the minimum and maximum values of the average annual changing rates of regional GDP during the 12th FYP period. Moreover, the 13th FYP sets multiple national-level targets by 2020, compared with 2015, with an increase of more than 50 million in the number of new urban employed persons, decrease of 15% in the energy consumption per unit of GDP, mitigation of 18% in carbon emissions per unit of GDP, limitation of 670 billion cubic meter on total water use, as well as reductions of 15%, 15%, 25%, 10%, and 10% in SO_2, NO_x, SD, COD, and AN emission loads, respectively. In this study, we consider national policy targets rather than provincial targets due to data availability issues.

The original environmental pollutant emissions are valued in metric tons, but the same physical unit-valued emission loads of different pollutants have varying adverse impacts on the environment. Thus, the physical unit-valued emission loads are standardized in equivalent units through division by equivalent units. The equivalent units published by China's Ministry of Environmental Protection are listed in table S2.

3. Results

3.1. Policy consistency: the employment policy unidirectionally obstructs the reduction of energy consumption and carbon emissions

The initial payoff matrix and the corresponding compromise solution in the baseline scenario are shown in table 1. The first row displays various objectives. Considering that the current pollutant emission reduction targets concentrate on five major pollutants (SO_2, NO_x, SD, COD, and AN) in China, although the objective function of minimizing pollutant emissions includes all 16 pollutants, we only consider these five pollutants when comparing solutions with policy targets. The third and last rows list policy targets of various objectives and compromise solutions, respectively.

According to the solutions of a single-objective linear programming model, the objectives of employment, energy consumption, and carbon emissions have improved potentials, since not all single-objective linear programming models can achieve those three policy targets. For instance, maximum employment is achieved at the cost of excessive energy consumption and degraded environmental quality, since the optimal energy consumption and carbon emissions are 4605 million tce and 11 726 million metric ton, which are 185 million tce and 748 million metric ton greater than the targets, respectively. In addition, from column 4 and columns 6–10, we see that the targets for water use and the main environmental pollutant emissions can be achieved synergistically when optimizing other objectives, indicating these two targets are loose constraints and can be tightened.

However, the compromise solution balances each objective and provides a reconciling pathway. From the compromise solution (the last row in table 1), we can see that employment fails to meet the target. Thus, an employment constraint is added to model (1) in the employment-dominated scenario. The results are given in table S3, indicating that employment can meet the policy target under the employment constraint. Compared with the baseline scenario, increased energy consumption, water use, and carbon emissions in the employment-dominated scenario indicates that the increased employment is at the expense of greater consumption of energy and water, as well as more carbon emissions. Due to this trade-off effect, the energy consumption and carbon emissions of the compromise solution in the employment-dominated scenario are off their targets. Hence, constraints of the energy consumption and carbon emission targets are added in the energy-consumption-dominated and carbon-emission-dominated scenarios, respectively. The results of these two scenarios are shown in tables S4 and S5.

Synergies and trade-offs among various policy targets drawn from compromise solutions in the three specific scenarios are illustrated in figure 2. Compared

Table 1. Payoff matrix, policy targets, and compromise solutions in the baseline scenario.

Objectives	Employment	Energy consumption	Water use	Carbon emissions	SO_2	NO_x	SD	COD	AN
Units	Million people	Million tce	Billion m3	Million metric ton	Million equivalent-kg				
Targets	825	4420	643	10978	16634	16562	5291	20012	2586
Maximizing employment	827	4605	616	11726	7209	10655	2974	10354	1668
Minimizing energy consumption	804	4299	588	10583	6738	9749	2829	10246	1660
Minimizing water use	780	4430	574	10922	6899	10105	2800	9580	1592
Minimizing carbon emissions	800	4337	585	10487	6737	9740	2819	10153	1648
Minimizing pollutant emissions	777	4411	587	10753	6767	9818	2739	9319	1566
Compromise solution	797	4314	581	10542	6747	9773	2808	10040	1639

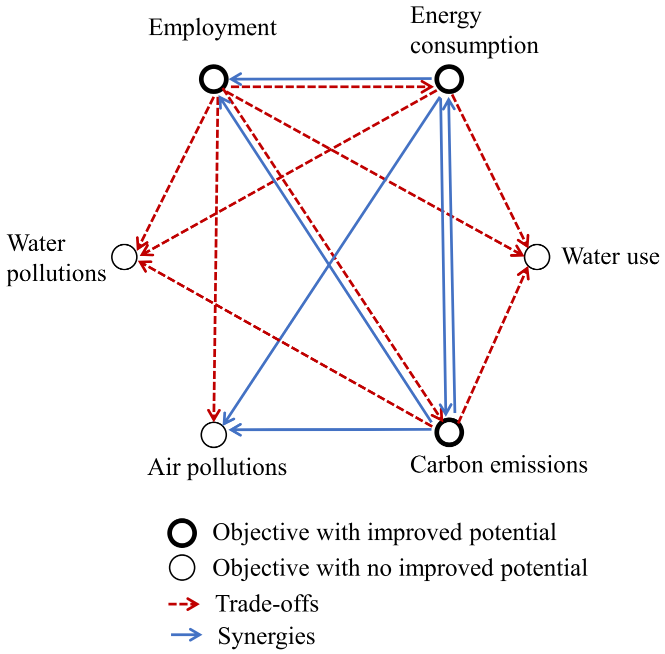


Figure 2. Synergies and trade-offs among various objectives. In this figure, environmental pollutant emissions are divided into air pollution (SO_2, NO_x, and SD) and water pollution (COD and AN).

with the baseline scenario, the effects of the employment policy on the other five objectives are negative because of the increased energy consumption, water use, carbon emissions, air pollution, and water pollution. The energy policy has positive effects on employment, carbon emissions, and air pollution, but has negative effects on water use and water pollution. Specifically, when the industrial restructuring pathway is dominated by the energy policy, employment, carbon emissions, and air pollution can be synergistically improved through energy conservation, while water use and water pollution deteriorate. In addition, the carbon policy facilitates an increase in employment, as well as a decrease in energy consumption and air pollution at the cost of increasing water use and water pollution. Thus, the carbon policy has positive effects on employment, energy consumption, and air pollution, but has negative effects on water use and water pollution.

Figure 3 indicates the compliance degree for each policy target of single-objective solutions and compromise solutions for each scenario. The exact results are shown in tables S3–S5.

Looking at the compromise solution, employment in the baseline scenario (figure 3(a)), energy consumption and carbon emissions in the employment-dominated scenario (figure 3(b)), as well as employment in the energy-consumption-dominated scenario (figure 3(c)) and carbon-emission-dominated scenario (figure 3(d)) cannot achieve the policy targets. Specifically, both energy consumption and carbon emission targets can be achieved in the baseline scenario. Yet, the employment target's constraint makes energy consumption and carbon emissions exceed their targets by 1.86% and 2.51%, respectively. This means that the employment policy counters energy consumption and carbon emissions. However, although employment in the baseline scenario is 797 million people (see figure 3(e)), falling behind the policy target (825 million people) by 3.39%, the constraints of energy consumption and carbon emission targets do narrow down the employment gap of the baseline scenario by 10.71% and 7.14%, respectively, with 800 million employed people in the energy-consumption-dominated scenario and 799 million employed people in the carbon-emission-dominated scenario (see figure 3(e)). This means that the employment policy hampers the reduction of energy consumption and the mitigation of carbon emissions, but not vice versa.

3.2. Trend adaptation: pathways dominated by energy and environmental policies conform to the national industrial development trend

The adjustment of industrial structure shows obvious differences based on different policy target scenarios, as illustrated in figure 4. When national development mainly focuses on social economy by way of increasing employment, the total outputs of most secondary industry sectors increase, while that of tertiary industry sectors decrease, compared with the no-policy-oriented baseline scenario. The total outputs of petroleum and gas (code 03), electronic equipment (code 19), wholesale and retailing (code 26), and other services (code 30) decline sharply by 13.01%, 19.69%, 14.67%, and 12.90%, respectively. Meanwhile, the manufacturing industry, which includes electricity and hot water production and supply (code 22), gas

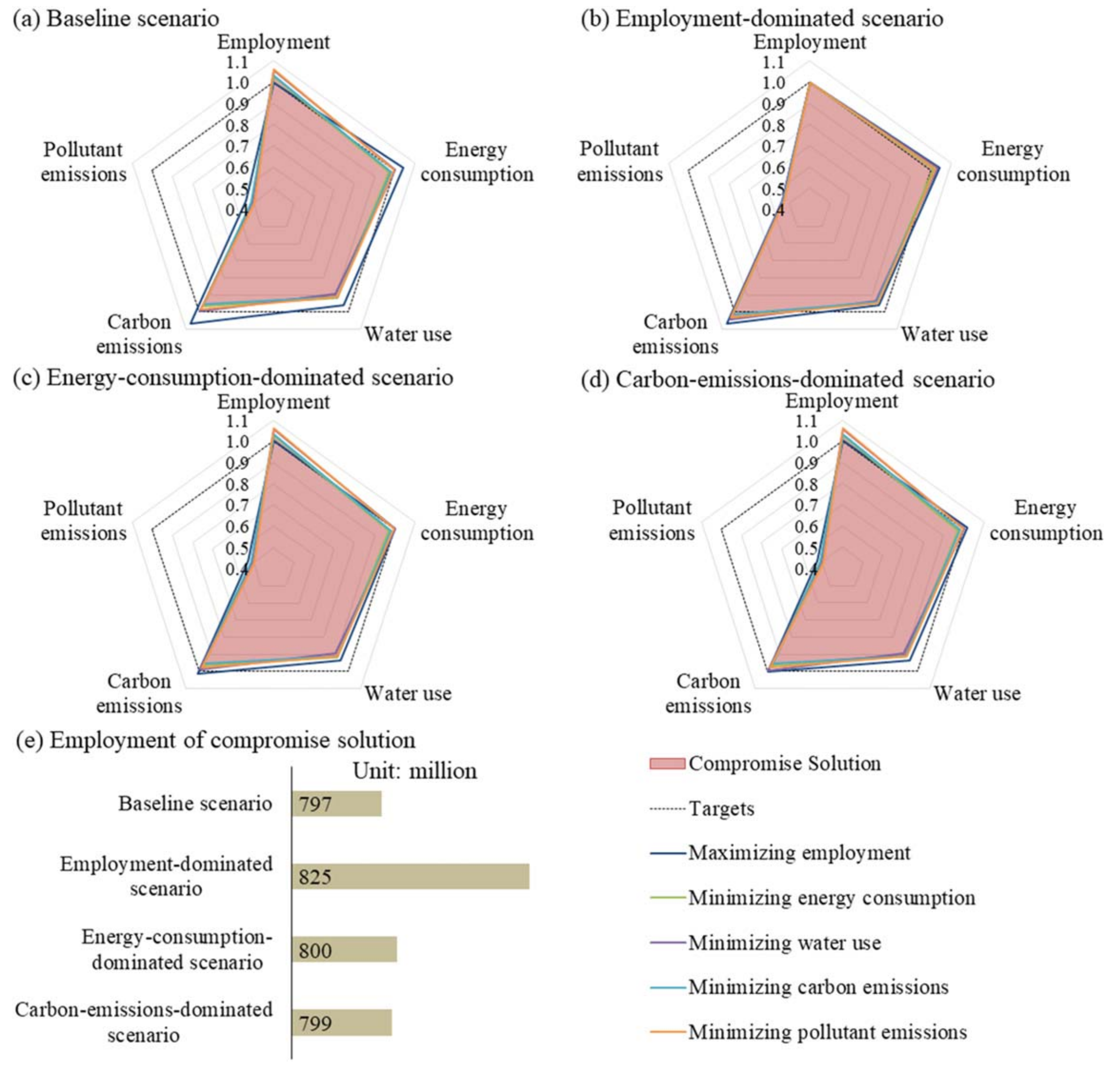


Figure 3. Radar diagram of each objective in the (a) baseline scenario, (b) employment-dominated scenario, (c) energy-consumption-dominated scenario, and (d) carbon-emission-dominated scenario. Absolute amounts are transformed to indexes, with targets equal to 1. The employment index is calculated by dividing the policy target by the absolute amount, while other indexes are measured by dividing the absolute amounts by the policy targets. The dotted line denotes the policy target standard; the solid line represents the objectives of single-objective solutions; while the filled area depicts the objectives of the compromise solution. Here, pollutant emissions contain only the five major environmental pollutants. The objective inside the target area is satisfactory; otherwise, the objective needs to be added in the constraints. Additionally, a bar chart of employment for the compromise solution in different scenarios is illustrated in (e). Detailed data on total outputs and the five objectives of each sector in each province are added in 'supplemental data.xlsx', which can be used as a reference for industrial restructuring for each province.

and water production and supply (code 23), and construction (code 24), experiences noteworthy growth (higher than 10.00%) in total outputs.

When the key point of the national development strategy is to cut down energy consumption and mitigate carbon emissions, the swings in sectoral total outputs become gentle. First, the percentage changes of total outputs in all sectors are within ±10%. Second, sectors that need to adjust their total outputs are limited, and most sectors just need to maintain their current production levels. In these two scenarios, sectors with enhanced or declining total outputs show similarity. Industrial sectors with high energy consumption and high emissions, such as coal mining (code 02), nonmetal mining (code 05), and transport and storage (code 25), are required to cut down their output levels. Meanwhile, the percentage changes of total outputs in certain sectors reveal heterogeneity. For example, the total output of electrical equipment (code 18) decreases in the energy-consumption-dominated scenario but increases in the carbon-emission-dominated scenario, while the total output of hotel and restaurant (code 27) behaves the opposite way.

3.3. Regional equity: the pathway dominated by the energy policy is conducive to regional equity

From a multi-regional perspective, the restructuring pathways of total outputs by region vary under the three scenarios. Figure 5 illustrates changes of total outputs by province in the three scenarios, compared with the baseline scenario. The total outputs of most regions increase when the employment constraint is

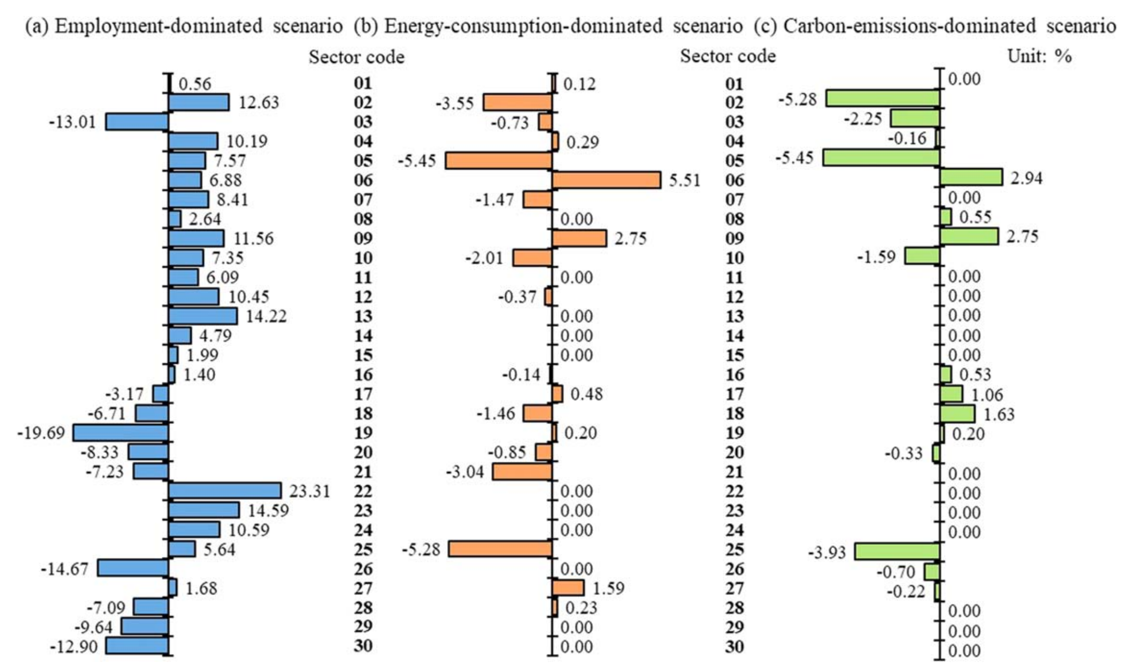


Figure 4. Percentage changes of sectoral total outputs under different scenarios, compared with the baseline scenario. The codes and the corresponding sectors are provided in table S1.

added, except for the constant total output in Shaanxi and the decreased total outputs in Beijing, Tianjin, and coastal provinces (see figure 5(a)). In the energy-consumption-dominated scenario (see figure 5(b)), provinces with constant total outputs lead the industrial reconstruction. Provinces in the central region, such as Inner Mongolia, Hubei, Hunan, Guangxi, and Jiangxi, are prioritized to improve their production levels; meanwhile, Liaoning, Tianjin, and Henan should retrench their production levels. From figure 5(c) we can see that only Hubei and Hunan benefit from the carbon emission mitigation targets, while Heilongjiang, Liaoning, Hunan, Shaanxi, Qinghai, and Hainan sacrifice their total outputs. Given the geographical distribution of developed provinces in the east and underdeveloped provinces in the west of China, the industrial restructuring pathway dominated by the energy consumption policy is conducive to regional equity.

4. Discussion

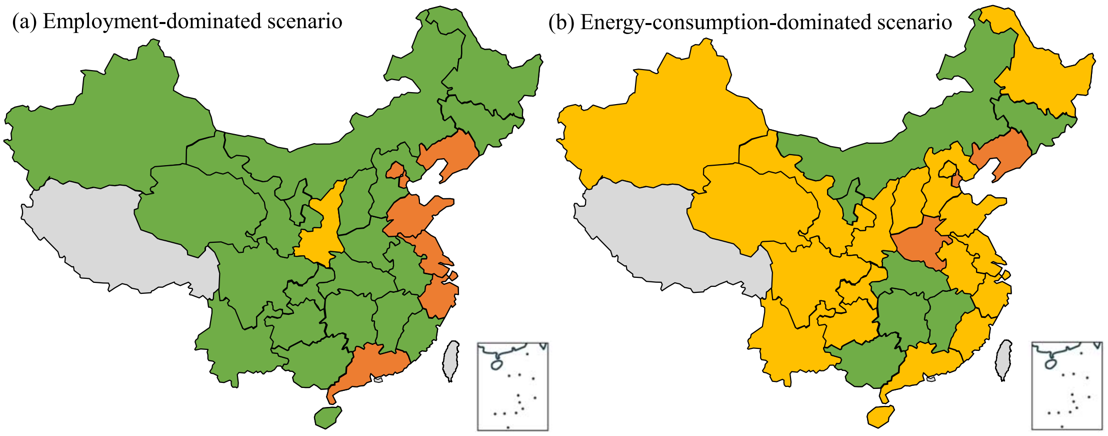
4.1. Policy interaction

First, the water use and pollutant emission policies demonstrate universal synergy since these two policy targets can be achieved in the process of realizing any other target. Second, the synergies and trade-offs among competing policy goals are not bidirectional. Energy consumption, water use, carbon emissions, and pollutant emissions increase when employment improves. However, the direction of the negative effects of the employment policy on the other objectives is irreversible because of the positive effects of the energy and carbon policies on employment. Third, because severe pollutant emissions are triggered by the coal-oriented energy consumption structure, the energy-consumption-dominated and carbon-emission-dominated scenarios have synergies in the mitigation of carbon emissions, conservation of energy, and reduction of pollutant emissions. Fourth, water resource has a substitution effect on energy; for example, hydropower could replace thermal power. Hence, reducing energy consumption or carbon emissions increases water use and water pollution.

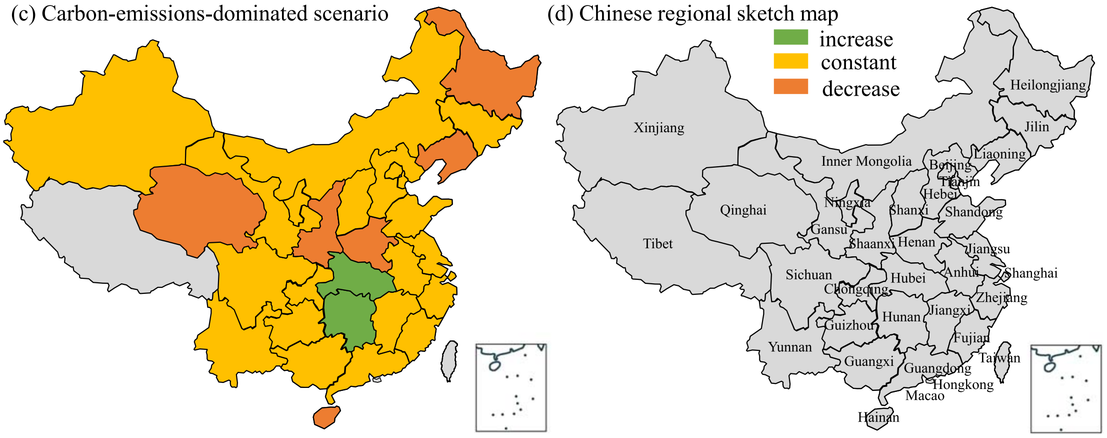
4.2. Policy priority

Considering consistency with other objectives, the employment policy shows negative impacts on all other objectives, while the energy and carbon policies increase employment as well as decrease energy consumption and carbon emissions. Thus, the energy and carbon policies lead to better synergy for the realization of other policy targets.

From a multi-sectoral viewpoint, the employment-dominated scenario advocates the development of the secondary industry but suppresses that of the tertiary industry. Given that the secondary industry sectors are mostly resource intensive and low value-added, while the tertiary industry sectors are capital intensive and high value-added, the secondary-industry-oriented development mode driven by the employment policy is not in line with the guideline for the optimization of the national industrial structure. Meanwhile the energy and carbon policies restrain outputs in high-energy-consumption and high-emission sectors and facilitate the development of high-value-added sectors. Additionally, the extent of the


(a) Employment-dominated scenario

(b) Energy-consumption-dominated scenario


(c) Carbon-emissions-dominated scenario

(d) Chinese regional sketch map

Figure 5. Diagram of the change in total outputs by province under the (a) employment-dominated scenario, (b) energy-consumption-dominated scenario, and (c) carbon-emission-dominated scenario. Changes within $-1\%\sim1\%$, higher than 1%, and lower than -1% are defined as constant, increasing, and decreasing, respectively. Grey areas in the first three subgraphs are not analyzed due to unavailability of data. The fourth subgraph (d) is the Chinese regional map marked with the provinces' names.

energy policy- and carbon policy-directed industrial restructuring is mild. In general, small-scale adjustments, the suppression of development in high-energy-consumption and high-emission sectors, as well as the promotion of development in high-value-added sectors, make the industrial restructuring pathway (driven by the energy and carbon policies) conform to the national industrial development trend.

From a multi-regional viewpoint, the employment policy inhibits the total outputs of economically flourishing provinces in the eastern costal region, while the carbon policy restrains that of developing provinces in the midwest and northeast regions of China. This widens the development gap and leads to regional inequity. Yet, the energy policy increases the total outputs of economically backward provinces in the central and northeast regions of China and keeps constant those of the developed provinces in the eastern costal region. Hence, regional development, as affected by the energy policy, is in accordance with the regional development orientation.

5. Conclusions

The year 2020 is the last year of the 13th FYP as well as a crucial period for China's sustainable economic transition. To achieve balanced development of the society, economy, energy, resources, and environment, the Chinese government has set several policy targets. As the last year of the 13th FYP approaches, how to improve the sectoral production structure in each Chinese province with the minimum regional inequity to balance conflicting national targets demands a prompt solution. Therefore, a multi-objective optimization model based on MRIO analysis is applied to design an industrial restructuring pathway for the Chinese economy, considering the consistency of each policy target, adaptation to the national industrial development trend, and regional equity. Moreover, based on the synergies and trade-offs resulting from various competing policies, how to prioritize policy choices is discussed.

The adjusted industrial structure under the policy scenario dominated by energy consumption has the best policy consistency, is the most conforming to the national industrial development trend, and provides the highest regional equity among the various policy-dominated scenarios. First, the compromise solution of minimizing energy consumption satisfies the complex policy targets of water use, carbon emissions, and pollutant emissions, and simultaneously minimizes the insufficiencies concerning the employment target. Second, the energy policy restrains the development of high-energy-consumption and high-emission sectors and facilitates the development of high-value-added sectors. Third, the energy-consumption-dominated scenario balances the development in various regions by increasing the total outputs in undeveloped regions and maintaining those in most other provinces.

Overall, considering consistency with other policy targets, adaptation to the national industrial development trend, as well as regional equity, the energy-consumption-dominated scenario is the most satisfactory optimal pathway to reconstruct the industrial structure. Therefore, to realize sustainability, we recommend that policymakers prioritize the energy policy for industrial restructuring. The specific pathway for satisfactory industrial restructuring is presented in supplemental materials. Particularly under the guidance of the energy policy, the total outputs of sectors with high energy consumption and high emissions (e.g. coal mining, nonmetal mining, and transport and storage) would be limited, and the development of provinces in the central region would be promoted. Although this study focuses on China, the analysis framework can be a useful tool for other countries or regions in designing sustainable development pathways that consider policy consistency, trend adaptation, and regional equity. Furthermore, as global trade intensifies, the key to achieving global sustainability is to integrate global goals into national goals while keeping the balance among multi-national social, economic, energy, resources, and environmental goals. That is, achieving global sustainability requires unified management among the interconnected goals of interdependent countries. Thus, future research could extend this study to the global level with a long time series and shed light on solutions for reconciling long-term, competing goals among different countries. Considering that the supply chains among various sectors may have changed because of improvements in efficiency as driven by technological innovation, future study could reconstruct a technical coefficient structure by introducing technology upgrades to MRIO to better describe the current situation.

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Data availability statement

Any data that support the findings of this study are included within the article.

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