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Environmentally-extended input-output simulation for analyzing production-based and consumption-based industrial greenhouse gas mitigation policies

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HIGHLIGHT

- An environmentally-extended input-output simulation model is developed.
- Production-consumption rate indicator is proposed to support systematic optimization.
- Production- and consumption-based industrial GHG mitigation policies are analyzed.
- Industrial GHG mitigation policy for each industry is developed.
- Optimized emission reduction pathways across the entire system is identified.

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ABSTRACT

Industrial GHG mitigation policies are prevalent across the world to realize global greenhouse gas (GHG) emissions targets. It is essential to simulate the impacts of different policies on various industries in the socio-economic system to find out the most effective emission reduction pathways. In this study, an Environmentally-Extended Input-Output Simulation (EEIOS) model is developed to facilitate integrated GHG mitigation policy development for multiple industries from both production and consumption sides. In addition, a Production-Consumption Rate is proposed to reflect the differences between Production-Based Policies (PBP) and Consumption-Based Policies (CBP) for a certain industry, which further supports the optimized and systematic emission reduction strategy development. A special case study of the Province in Saskatchewan, Canada, is conducted to illustrate the applicability and superiority of the Environmentally-Extended Input-Output Simulation model. It is found that Production-Based Policies applied to primary industries will lead to larger GHG reductions, and that Consumption-Based Policies should be applied to industries that are located at the end of industrial chains. The results provide a solid scientific basis for supporting industrial greenhouse gas mitigation policy development for each industry and identifying the optimized emission reduction pathways for the entire socio-economic system.

1. Introduction

Global greenhouse gases (GHG) emissions have significantly increased since 1900, which seriously affect the environment, human health, and the global economy [1]. Human activities are responsible for almost all of the increase in GHGs in the atmosphere over the last 150 years [2]. Facing this challenge, many countries have shifted their industrial economic activities to lower GHG emissions through the adoption of GHG mitigation policies [3,4].

Industrial GHG mitigation policies can be divided into two main types, including Production-Based Policies (PBP) and Consumption-Based Policies (CBP). With different mechanisms of emission reduction, the effects of PBP and CBP are different. In addition, the emission performances of different industries vary significantly due to their heterogeneous production structures. To find out the most effective emission reduction pathways, it is essential to simulate the impacts of

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different policies on various industries in a socio-economic system.

To mitigate GHG emissions, a broad spectrum of policy options exist from both a production and consumption perspective [5]. The PBP reduces the emissions through the production activities, such as technology mandates and environmental standards. For example, the iron and steel industry was one of the largest contributors to China's GHG emissions. Xu and Lin used the nonparametric additive regression model to examine the key driving forces of GHG emissions in China's iron and steel industry and provide decision support for the PBP development [6]. In Switzerland, the cement industry was among the top three industrial energy consumers and a major contributor to Swiss GHG emissions. A bottom-up analysis was conducted to estimate the energy savings potential for the cement sector and analyze the techno-economic barriers [7]. Renewable energy and energy efficiency technologies were emphasized for GHG mitigation in the electricity sector. Callaway et al., evaluated these in the United States in terms of carbon dioxide emissions displaced, operating costs avoided, and capacity value generated [8]. Carbon Capture and Storage (CCS) technologies were presented as a solution to reach ambitious climate targets. Based on a wide review of geological storage potential and various data, a TIAM-FR model was developed to discuss the implementation impact of CCS in various locations [9].

The CBP works through market-based regulations to reduce the consumption of emission-intensive commodities, including taxes on emissions, cap-and-trade, and subsidy programs. Fang et al., explored the carbon tax pilot in Yangtze River Delta urban agglomerations based on a novel energy-saving and emission-reduction system with carbon tax constraints [10]. An integrated economic and environmental model was developed to assess the impacts of the cold supply chain under carbon tax regulation [11]. Cap-and-trade policy for electricity networks would likely increase prices and decrease consumption of electricity. A two layer mathematical-statistical model was developed to pursue Pareto optimal designs for CO_2 cap-and-trade policies [12]. Xu et al., studied the production and pricing problems in make-to-order supply chains with cap-and-trade regulations. The results showed that the optimal total emissions would decrease and the optimal production quantities would increase [13]. Based on the literature review, it can be seen that most of the previous studies focused on one specific policy in a certain region. Meanwhile, most of them were seeking the most economic pathways for an industry under one certain policy, especially for consumption-based policy studies.

GHG emissions accounting is a prerequisite to support GHG mitigation policy development. So far, Production-Based Accounting (PBA) and Consumption-Based Accounting (CBA) are the most widely-adopted methods to evaluate GHG emissions in different jurisdictions. PBA follows the guidelines of the Intergovernmental Panel on Climate Change (IPCC), which calculates the GHG emissions from fossil fuels in a country by industrial production and household consumption [14]. Liu et al., re-evaluated China's carbon emissions using harmonized energy consumption, clinker production data, and two comprehensive sets of measured emission factors for coal [15]. Moreira et al., assessed the potential and cost effectiveness of negative emissions in the joint production system of ethanol and electricity based on sugar cane, bagasse, and other residues in Brazil [16]. CBA estimates the GHG emissions caused by final demand, which considers export and import activities [14]. The Multi-Regional Input-Output (MRIO) analysis has been accepted by the scientific community as an alternative to the IPCC accounting. The total CO_2 emissions due to consumption in 175 countries during the period 2008–2012 were estimated through the National Carbon Intensity method, with a focus on the Mediterranean area. The results were used to assign emission responsibility on the basis of each country's demand [17].

There is a controversial debate around the issue of whether GHG emissions inventories should be based on territory-related production or consumption [18,19]. To further explore the differences between production-based and consumption-based accounting, the two methods were both adopted in some previous studies. Based on the detailed carbon emission inventory, the input-output analysis (IOA) was applied to calculate both the production-based and consumption-based carbon emissions of Beijing [20]. Fan et al., explored the characteristics of production-based and consumption-based CO_2 emissions for 14 major economies through multiple-dimension comparisons to get insight into the emissions equity comparisons among major emitters [21]. PBA versus CBA of 110 countries were compared to analyze the reasons for the differences. In particular, the carbon leakage from developed to developing countries was investigated [14]. Simas et al., determined production- and consumption- based pressure indicators for GHG emissions using the EXIOBASE global MRIO model and investigated the correlation among different indicators to support the ranking of environmental performance of various countries [22]. Millward-Hopkins et al., implemented methodologies for assessing production- and consumption-based emissions at the city-level and estimated the associated emissions trajectories for Bristol, a major UK city, from 2000 to 2035 [23]. Besides GHG emissions, CBA and PBA were also used to calculate the black carbon emissions of four Chinese megacities in 2012. It was found that collaborative efforts to reduce emission intensity could be effective in mitigating climate change for megacities as either as producers or consumers [24]. The PBA and CBA studies mostly focused on the GHG emissions reduction responsibility allocation and the carbon leakage problems.

Computable General Equilibrium (CGE) models have been widely used in simulating the economy-wide effect of climate mitigation policies [25]. Zhou et al., developed a two-stage decomposition method and a static CGE model to trace and quantify the sources of rebound effects for different energy sources in China [26]. A CGE model of the Turkish economy that combines macroeconomic representation of non-electric sectors with a detailed power sector representation was developed to fully assess the impacts of the Paris Agreement pledges of Turkey under scenarios [27]. A CGE model for the Province of Saskatchewan, Canada was developed to examine and analyze a series of direct and indirect socio-economic impacts of a carbon tax [28]. Benavides et al., adopted both an energy sectorial model and a Dynamic Stochastic General Equilibrium model to analyze the economy-wide implications of a carbon tax applied on the Chilean electricity generation sector [29]. A global recursive dynamic CGE model was applied to evaluate how energy security and energy structure change under climate mitigation scenarios during the 21st century in East Asia [30]. To compare the cost of climate change policy consistent with the Paris Agreement targets and the cost of climate change induced agricultural productivity shocks, a dynamic CGE model for India was used to estimate the changes in various economic aspects [31]. However, considerable CGE mitigation modelling studies were channeled towards energy systems, while limited CGE modelling efforts were devoted to other important GHG emitting sectors [25]. In addition, the development of a CGE model must be based on the actual economic structure, which requires a large number of real economic data and cannot be applied in other areas.

Based on the Input-Output Analysis (IOA) proposed by Leontief, the Environmentally-Extended Input-Output (EEIO) model is widely-used to evaluate the GHG emissions in a macro-scale economy [32,33]. EEIO has been applied to analyze the inventories of energy and environmental burdens associated with a given product. Nagashima, Uchiyama, and Okajima provided a comprehensive analysis of the environmental, energy, and economic impacts of installing a wind power generation system [34]. To solve water shortages in China, an economic I-O life cycle assessment (LCA) model was adopted to assess and compare five Chinese rural toilet technologies on the basis of energy consumption and GHG implications [35]. Reutter et al., applied EEIO analysis to estimate environmental and economic factors embodied in Australian food waste in order to address food waste problems [36]. This study further reflected the benefits of EEIO as it provided inclusive information of all actors in the supply chain and enabled analysis of