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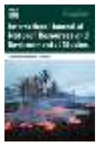

The Chemical Synergy of Greenhouse Gases and Cost-Effectiveness Analysis for Climate Mitigation Strategies

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ABSTRACT

Global warming is a serious challenge facing the world today. This study confirms that greenhouse gas emissions from human activities are the main driving factors. By systematically analyzing the source-sink balance of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4), it is clarified that the significant imbalance caused by the surge in emissions and the weakening of carbon sink capacity is the key mechanism for accelerated climate warming. Furthermore, from the perspective of chemical reaction kinetics, the synergistic effects among the three key greenhouse gases of hydroxyl radical (OH) regulation mechanism, nitrogen cycle cascade effect and sulfate aerosol effect were explained. On this basis, the economic benefit index (CEI) is innovatively constructed, and the above synergistic effects are integrated into the accounting framework. Taking CO and CH as an example, the paradigm of quantitative analysis using CEI is set up, and it is speculated that the synergistic reaction can significantly improve the CEI estimation. Finally, based on the quantitative results of CEI, a differentiated emission reduction strategy is proposed: give priority to the implementation of high CEI measures, and plan the long-term development path of low CEI technology. This study constructs a complete research system from cause analysis, chemical mechanism exploration to economic evaluation and strategy formulation, aiming to provide a theoretical framework and decision support for global climate governance.

KEYWORDS

Global warming, Environment, Greenhouse gases, Chemical Synergistic Effects, Cost-Effectiveness Index.

1. INTRODUCTION

1.1. Current status of global warming

Global warming has evolved from scientists ' early warning of the future to the current subversive reality. According to the World Meteorological Organization (WMO), 2024 was the hottest year on record. The global average temperature is about 1.55 C higher than the pre-industrial level, breaking the 1.5 C temperature control threshold set by the Paris Agreement (2015) for the first time (United Nations, 2015)[1]. This seemingly small numerical transcendence will actually lead to a cascade of ecological and social crises, indicating that the global climate system has broken through the 'relative security boundary ' recognized by the scientific community. A new study found that when the global temperature rises to 1.5 C, the probability of extreme high temperature events will increase to four times. After exceeding this threshold, the frequency of heat waves will surge to eight times, and the risk of compound climate disasters will increase significantly (Armstrong McKay et al., 2022)[2]. In addition, global warming may have caused irreversible melting of the Greenland Ice Sheet, and limiting global warming to between 1.5 C and 2 C could mean exceeding seven critical points, leading to the loss of alpine glaciers and disruption of key ocean currents (Armstrong McKay et al., 2022)[2]. The global average temperature from January to May 2024 is the second highest record in the same period since 1850. Chongqing, Sichuan and other places in China experienced extreme high temperatures exceeding 40 C in June 2025. Fundamentally, global warming originates from the chemical accumulation effect of greenhouse gases, and its impact focuses on three dimensions: public health safety, social and economic loss costs, and economic benefit evaluation of temperature control measures. This study reveals a novel research perspective: integrating chemical mechanisms and economic effects, and conducting interdisciplinary research to deepen the systematic understanding and discussion of global warming.

1.2. Relationship between global warming and chemistry

The essence of global warming is the destruction of the earth 's energy balance, and its core driving mechanism is derived from chemical processes. From greenhouse gas emissions, to its conversion, accumulation in the atmosphere and the resulting warming effect, chemical reactions run through: the release of CO_2 from fossil fuel combustion involves basic combustion chemical reactions; the capture of infrared radiation by greenhouse gases depends on specific molecular vibration modes; the magnitude of global warming also depends on the synergistic effect of various chemical reactions. At the same time, chemistry is not only used to explain the causes of climate problems, but also a key basis for governance strategies. For example, the carbon capture technology for reducing greenhouse gas CO_2 depends on the selective absorption reaction of amine compounds; artificial photosynthesis converts CO_2 into fuel through a catalytic pathway. Such core technologies for mitigating climate change are based on chemical principles. Therefore, this paper will explore the chemical mechanism behind global warming from a chemical perspective. Through in-depth analysis of key response pathways and strict adherence to the principle of ' problem root and solution homology ', it provides a solid scientific basis for climate governance.

1.3. Necessity of economic benefit analysis of global warming control based on chemical principles

The governance scheme based on chemical analysis has laid a scientific foundation for coping with global warming, but its effectiveness needs to be verified by economic benefit analysis. The Cost-Effectiveness Index (CEI) is a commonly used economic assessment tool to measure the ratio between the cost of interventions and their benefits. This study attempts to establish a relationship between CEI and chemical reaction mechanism, and evaluate the synergistic effect, temperature control potential and policy implementation cost of different chemical schemes through CEI means, so as to screen out the policy combination and implementation path with better cost-effectiveness.

1.4. Purpose of the Article

This paper will systematically study and analyze the chemical mechanism of global warming from a chemical perspective. The research content covers the basic properties of greenhouse gases and their source and sink processes, and then extends to the analysis of synergistic effects between multiple gases. By integrating economic cost factors, the potential economic benefits of different mitigation measures are comprehensively evaluated, and the most cost-effective solution is determined accordingly.

2. LITERATURE REVIEW

2.1. Greenhouse gas analysis behind global warming

In the existing research on the topic of global warming, the analysis of greenhouse gases has been very comprehensive. " Who is the main cause of global warming-the natural source of carbon emissions and geochemical cycle and the main cause of climate change research review " published by Jinglian Zhang analyzes the main causes of global warming, and puts forward that global warming is not only caused by human activities, but also the natural source of carbon emissions plays an important role in climate change. Detailed information on the role of carbon in the geochemical cycle is provided, including the effects of natural processes such as volcanic activity, plant respiration, and ocean uptake on atmospheric carbon dioxide concentrations. (Zhang, J., Du, L., & Li, X, 2012)[9]. In the paper " Study on the accumulation effect and influencing factors of greenhouse gases in frozen reservoirs, "Miaomiao Liao further observed greenhouse gases in the real environment. Through the monitoring of greenhouse gases (CO2, CH4, N2O) in Tanghe Reservoir of Liaoning Province, the temporal and spatial variation characteristics of these gases in different seasons and frozen periods were revealed, which provided a new perspective for the study of the greenhouse effect. The study found that the greenhouse gas emissions of the reservoir showed obvious seasonal and spatial distribution characteristics. Especially during the freezing period, CH4 accumulated significantly at the ice-water interface, and the longer the freezing time, the greater the concentration and emission flux increased. By the time of spring ice melting, CH4 emissions have risen sharply, which reveals that winter accumulation and spring ice melting are the key periods of greenhouse gas emissions. These greenhouse gas emissions contribute significantly to the greenhouse effect in the reservoir area. According to the global carbon budget report and China 's carbon emission trends over the years, the annual cumulative emissions of CO2, CH4 and N2O are 263.64 g/(m2 a), 1.35 g/(m2 a) and 1.01 g/(m2 a), respectively, and the comprehensive warming potential is 597.32 gCO2/(m2 a). This data reflects China 's importance in global greenhouse gas emissions. (Liao, M. 2021)[7]. In addition, the existing analysis of the gas effects behind global warming mostly focuses on the role of a single greenhouse gas. As Hong Liao, Xiaobo Ren, Quansheng Ge and other scholars pointed out in the 'New Understanding of Climate Warming and Its Sensitivity to Carbon Dioxide Concentration-Research Progress of the Climate Sensitivity Task Group of the Strategic Priority Science and Technology Project of the Chinese Academy of Sciences' Carbon Budget Certification and Related Issues in Response to Climate Change ', the continuous increase in the concentration of carbon dioxide (CO2) in the atmosphere leads to global warming, which has aroused widespread concern in the international community. The 2009 Copenhagen conference shifted the 2 C threshold from a scientific understanding to a political consensus that the future global average temperature increase relative to the pre-industrial revolution should be controlled within 2 C, while the atmospheric carbon dioxide equivalent concentration should not exceed 450 ppm. The correspondence between global temperature change and greenhouse gas concentration has become the logical starting point for formulating emission reduction targets, which essentially reflects the problem of carbon dioxide emission space. The Climate Sensitivity Task Group of the Chinese Academy of Sciences has obtained a series of new understandings on climate sensitivity by obtaining basic data on climate change, developing and improving the climate system model of the Chinese Academy of Sciences, and predicting the concentration and occurrence time of greenhouse gases corresponding to the global 2 C warming. This study expounds on the impact of rising carbon dioxide concentrations on global warming, especially how to keep the global temperature increase within 2℃ in the context of addressing climate change. The research, by obtaining basic data on climate change, developed a complete climate system model of the Chinese Academy of Sciences, and predicted the concentration and change time of greenhouse gases under the 2 C warming target, proposed a new understanding of climate sensitivity (Liao, H., Ren, X., Ge, Q., et al. 2020)[6].

2.2. Cost-Effectiveness Indicator

Many existing studies on environmental science have tried to use cost-effectiveness index analysis. Among them, Dongyang Zhao, Yana Jin and Shiqiu Zhang 's study ' Cost-effectiveness Analysis of Pollution Reduction in Coal-fired Power Plants and Discussion on Ultra-low Emission Policies ' used cost-benefit assessment methods to deeply analyze the economy of pollutant emission reduction in coal-fired power plants, and discussed the implementation effect of ultra-low emission policies. This study echoes the previous reports ' Application and cost-benefit analysis of ultra-low emission technology in air pollution control in coal-fired power plants in 2025 ' and ' Technical and economic analysis of ultra-low emission transformation of large coal-fired power plants ', and emphasizes the application of ultra-low emission technology in coal-fired power plants and its positive impact on the environment and economy. This study provides an application example for the cost-effectiveness analysis method, focusing on the analysis of the economics of different pollutant emission reduction paths (Dong, D., Jin, Y., & Zhang, S. 2016)[3].

2.3. The research significance of greenhouse gas interactions and CEI cooperative analysis

Through the ' study on the cumulative effect and influencing factors of greenhouse gases in frozen reservoirs ', it has produced an inspiration on whether there is a synergistic effect between greenhouse gases. Perhaps the strength of the greenhouse effect is related to the chemical reaction after gas emissions. More importantly, the ' new understanding of climate warming and its sensitivity to carbon dioxide concentration-the research progress of the climate sensitivity task group of the strategic leading science and technology project of the Chinese Academy of Sciences ' carbon budget certification and related issues in response to climate change ' will focus more on the role of carbon dioxide, so that the impact of other greenhouse gases (such as methane and nitrous oxide) is not analyzed. However, there may be complex interactions and feedback effects between them, such as synergistic effects in chemical reactions. In addition, the contribution of different greenhouse gases to climate warming is different. The greenhouse effect of methane is more than 80 times that of carbon dioxide, and the change of its concentration has a significant impact on climate change. For example, the United Nations World Meteorological Organization notes that methane contributes up to a third of today 's warming, and that its global warming potential is more than 80 times that of carbon dioxide in the 20 years after it is released into the atmosphere. In order to comprehensively assess the overall picture of climate change, in-depth analysis of a single gas is necessary, but the mutual reaction and integration between multiple gases is also worth considering. In this context, this study proposes a new multi-perspective perspective, which aims to simulate the climate effect more comprehensively by considering the interaction of multiple greenhouse gases.

Global warming research mainly focuses on the direct impact of greenhouse gases, and pays less attention to the comprehensive consideration of chemical mechanism and economic benefit analysis. In response to this problem, this paper proposes a new perspective: this perspective is based on the climate effect of chemical mechanisms, comprehensively considers the synergistic effect of greenhouse gases, and introduces economic feasibility analysis (Cost-Effectiveness Indicator) to quantify the correlation between climate effects and economic costs. This interdisciplinary approach contributes to a comprehensive understanding of the climate change mechanism and provides a theoretical basis for precise and sustainable emission reduction policies.

3. THE CHEMICAL BACKGROUND AND SYNERGISTIC EFFECTS OF GLOBAL WARMING

3.1. Analysis of the causes of global warming and greenhouse gases

When considering global climate change, the basic factors affecting the earth 's climate are solar radiation, atmospheric circulation and surface conditions. Solar radiation dominates and provides energy for climate processes. Global climate differences and changes are mainly due to their uneven distribution and changes. The atmospheric circulation controls the weather and climate according to the principle of air thermal expansion and contraction. The differences in surface conditions lead to climate differentiation (Li, G. C. 2005)[10]. However, the global climate has been significantly warming in the past century, and 2024 is recognized as the hottest year on record. The global average temperature is about 1.55 degrees Celsius higher than the pre-industrial level, becoming the first year in which the global average temperature is 1.5 degrees Celsius higher than the pre-industrial level. During the period from 2023 to 2024, the temperature has reached new highs, which is difficult to explain only by the three basic factors of natural change. Since the industrial revolution, the trend of global warming has been increasing. Scientists have confirmed the significant impact of human activities on climate change through observational facts and climate model predictions. For example, the IPCC Fifth Assessment Report pointed out that global warming caused by human activities is beyond doubt. In addition, the simulation results of the CMIP6 model show that the global average near-surface temperature from 2010 to 2019 increased by 1.1°C compared with that before the industrial revolution, and the temperature rise caused by human activities was 0.9°C-1.3°C.

Since the industrial revolution, the intensity of human activities has increased greatly, population expansion has promoted urbanization, industrialization and transportation modernization, and the consumption of natural resources has increased exponentially. In this process, two major effects are significant: First, human activities have caused greenhouse gas emissions in the atmosphere to continue to rise; second, the rapid growth of the population has led to excessive deforestation of forests, which has weakened the ecological functions of forests and exacerbated the impact of the greenhouse effect. In summary, human activities are the core cause of global climate change, and the increase of greenhouse gas concentration is the key mechanism driving global temperature rise. Greenhouse gases (GHGs) can absorb and release infrared radiation from the earth 's surface, play a role in heat preservation of the earth 's surface, and are natural elements to maintain the appropriate temperature of the earth (IPCC, 2023)[5]. However, human activities have made its concentration abnormally high, which has become the core factor of global warming. The principle of the greenhouse effect involves the solar short-wave radiation causing the surface to heat up, the surface long-wave radiation releasing energy, and the greenhouse gas absorbing long-wave radiation and reflecting part of the heat back to the surface, thereby reducing heat loss and maintaining temperature balance. This process is similar to the Earth being wrapped in a warm blanket, in which greenhouse gases such as carbon dioxide, methane, and water vapor play a key role in absorbing and re-emitting infrared radiation, preventing the Earth 's heat from spreading and keeping the Earth 's surface warm (Houghton, 2004)[4]. This process is like a glass greenhouse retaining heat. Once the emission is excessive, it will aggravate the greenhouse effect and cause the global temperature to rise.

Among the many greenhouse gases, several types are particularly important. Carbon dioxide (CO2) mainly comes from the combustion of fossil fuels, and it has been retained in the atmosphere for 50 to 200 years, which contributes significantly to the warming effect caused by human activities. According to the data of the World Meteorological Organization, the global average surface carbon dioxide concentration has reached 420 ppm in 2023, an increase of 11.4 % compared with 20 years ago, and the accumulation rate of carbon dioxide in the atmosphere exceeds any period in human history (IPCC, 2023)[5]. Scientific research shows that carbon dioxide, as a long-lived greenhouse gas, may continue to warm up the global temperature for decades even if its emissions are reduced to net zero in the future. As a powerful greenhouse gas, methane (CH) is mainly derived from agricultural activities, and its retention time in the atmosphere is about 12 years. Compared with carbon dioxide, the 100-year warming potential per unit molecule of methane is more than 80 times that of carbon dioxide (United Nations World Meteorological Organization, 2022), and contributes up to one-third of the current climate warming. Nitrous oxide (N2O), as the third largest greenhouse gas in the world, is mainly derived from activities such as agricultural fertilization. According to the Global Emissions Database for Atmospheric Research (EDGAR), global N2O emissions in 2023 are about 2.5 billion tons of carbon dioxide equivalent (CO2e), accounting for about 5 % of global greenhouse gas emissions. The 100-year warming potential of N2O is about 273 times that of carbon dioxide, and the retention time in the atmosphere is about 120 years. In addition, the emission of N2O will seriously deplete the ozone layer and pose a threat to human health. The analysis shows that the existence time and warming effect of different greenhouse gases in the atmosphere are different. Carbon dioxide, Methane and nitrous oxide directly affect the Earth 's climate change and play an important role in the global carbon cycle. Moreover, the change of greenhouse gas concentration not only depends on human emissions, but is also closely related to the ' source ' and ' sink ' of nature.

3.2. Sources and sinks of greenhouse gases

Earth 's natural activities are important natural sources of greenhouse gases, and their release pathways are diverse and involve multiple gas types. Volcanic activity is one of the main contributors. The total amount of carbon dioxide released by volcanic eruptions and calmness in the world is about 9.0 × 10 tons per year. This data covers a variety of greenhouse gases such as carbon dioxide and methane. For example, the Pinatubo volcano in the Philippines released about 2.0 × 10 Ω t CO2 in an eruption, while the Etna volcano in Italy released about 2.5 × 10 Ω t CO2 in a quiet way every year. However, the amount of carbon dioxide emitted by volcanoes is relatively small compared to human activity. According to research, the annual carbon dioxide emissions generated by human activities are 40 to 100 times that of all volcanic emissions. Mud volcanoes are dominated by methane emissions, with global annual emissions estimated at 1.0 × 10 - 2.0 × 10 ton, typically represented by mud volcanoes near Baku. Similarly, earthquakes and related processes in geological activities will also release greenhouse gases. When earthquakes occur, they are often accompanied by the release of natural gas. The " boiling " of seawater in the Chile earthquake, the correlation between the Wenchuan earthquake and the natural gas explosion all reflect this. Similarly, the serpentinization process of the mid-ocean ridge and oceanic crust cannot be ignored. The former releases 1.6 × 10 m3 of methane per year, while the latter releases about 9.0 × 10 t of methane per year globally. In addition, deep geological environments such as metal deposits and coal mines release methane, carbon dioxide, etc., which further constitute the natural emission pathway of greenhouse gases (Zhang, J., Du, L., & Li, X, 2012)[9].

Continuing to consider the natural state, there are multiple key greenhouse gas sinks in the earth system, which constitute an important regulation mechanism for greenhouse gases such as carbon dioxide (CO2) in the atmosphere through multi-sphere synergy. The ocean is an important carbon sink. According to the latest global circulation carbon cycle model, it is estimated that in the 1980 s, the amount of CO2 absorbed in the atmosphere was 1.5 ~ 2.2 GtC per year, equivalent to 1.5 × 10 - 2.2 × 10^9tons. At the same time, the biological carbon sequestration capacity of the ocean can reach 4.0 × 10^{10} tons per year. As one of the largest and most active carbon pools in the Earth 's surface layer, the soilsphere stores about 1.55 × 10^{12} tons of organic carbon. Although the annual release of CO2 to the atmosphere is 10 times that of fossil fuel combustion, its strong carbon sequestration potential makes it a key source and sink system for atmospheric CO2. For example, the research team of Northeast Forestry University constructed a global map of soil mineral-associated organic carbon and particulate organic carbon storage and turnover for the first time, which provided an important scientific basis for improving soil organic carbon storage and helping ' carbon neutrality '. The carbon sink effect of forest and terrestrial vegetation is significant. For example, in 2004, the amount of CO2 absorbed by China 's forests accounted for 8 % of the total fossil fuel emissions in China. From 1981 to 2000, the total carbon sink of China 's terrestrial vegetation and soil can reach 20.8 % ~ 26.8 % of the industrial CO2 emissions in the same period. In addition, geological processes such as lithospheric weathering are further involved in the fixation of greenhouse gases through long-term carbon cycle (Zhang, J., Du, L., & Li, X, 2012)[9].

Before industrialization, natural sources and natural sinks maintained a dynamic balance, so that the concentration of various greenhouse gases remained relatively stable. Since the industrial revolution, anthropogenic emissions sources have increased significantly, breaking this balance. Specifically, the combustion of fossil fuels (such as coal, oil, and natural gas) releases carbon stored in geological history, resulting in a continuous increase in atmospheric CO2 concentration. Industrial processes (such as cement production and chemical manufacturing) directly emit CO 2, N 2 O and other gases; the industrialization of agriculture and animal husbandry (e.g., excessive application of chemical fertilizers) increased N2 O and CH2 emissions. According to the latest data from the Keeling Curve, the monthly average concentration of carbon dioxide in the atmosphere is 4.7 ppm higher than a year ago, a record increase. This trend is significantly positively correlated with human energy consumption and population growth. Fossil fuel combustion and deforestation are the main reasons for the rapid growth of global carbon dioxide concentration. At the same time, the absorption capacity of natural sinks did not increase synchronously, or even showed a weakening trend. For example, terrestrial vegetation, as an important carbon sink, its ability to sequester carbon through photosynthesis is severely constrained by deforestation (due to the expansion of industrial and residential land) and climate change (such as an increase in extreme weather events). Some areas have even changed from carbon sinks to carbon sources, and some areas of the Amazon rainforest are typical examples of this change. Therefore, the concentration of greenhouse gases continues to rise, driving global warming through the radiative forcing effect.

3.3. We can analyze the warming effect among greenhouse gases by means of the synergistic effect of chemical formulas

Synergistic effect refers to the phenomenon that the combined effect of two or more factors exceeds the sum of their independent effects when they interact with each other. In the context of climate change, the chemical and physical interactions between greenhouse gases can significantly enhance the global warming effect. For example, the increase of a certain greenhouse gas concentration may inhibit the removal process of another greenhouse gas through chemical reaction, or promote its formation, thus forming a positive feedback cycle and aggravating the imbalance of the climate system. As mentioned above, some of the greenhouse gas emissions caused by human activities that destroy the balance can undergo such synergistic effects, and such cascade effects can be reflected in multiple chemical reactions.

3.3.1. OH free radical regulation mechanism

As the 'natural cleanser 'of the atmosphere, the concentration of OH radical directly determines the atmospheric lifetime of greenhouse gases.

$$CH_4 + OH \rightarrow CH_3 + H_2O \text{ (k=6.2×10}^{-15}\text{ cm}^3\text{ molecule}^{-1}\text{ s}^{-1}\text{ at 298K)} \quad (1)$$

$$CO + OH \rightarrow CO_2 + H \text{ (k=2.4×10}^{-13}\text{ cm}^3\text{ molecule}^{-1}\text{ s}^{-1}\text{)} \quad (2)$$

$CH_4$and CO released by human activities break this balance by competitively consuming OH. It is shown that the reaction rate constant of CO with OH (2.4×10^{-13} $cm^3\cdot molecule^{-1}\cdot s^{-1}$) is two orders of magnitude higher than that of $CH_4$with OH (6.2×10^{-15} $cm^3\cdot molecule^{-1}\cdot s^{-1}$), which significantly enhances the OH consumption capacity of CO. Therefore, the preferential consumption of CO leads to the increase of the lifetime of CH4 and the accumulation of CH4 in the atmosphere. At the same time, when the concentration of CH4 increases (human factor), its reaction with OH will further reduce the stock of OH, resulting in the weakening of atmospheric cleaning capacity. Not only the lifetime of CH4 itself is prolonged, but also the degradation process of other greenhouse gases such as O3 is also blocked (CH4 is an active gas and promotes the formation of O3 on the ground. O3 will inhibit the absorption of CO by plants and indirectly increase the concentration of CO), which ultimately aggravates the impact of the greenhouse effect. The model calculation confirms that for every 10 % increase in atmospheric CO concentration, the CH lifetime will be extended by about 0.8 years, forming a vicious cycle of " warming gas accumulation-cleaning ability decline. "

3.3.2. Cascade reaction of nitrogen cycle

As another key greenhouse gas, the chemical decomposition of N2O will lead to a chain reaction of ozone depletion. The depletion of the ozone layer will lead to UV uptake, resulting in warming while inhibiting the growth of marine plankton and the photosynthesis of terrestrial plants, resulting in a decrease in the ability to absorb carbon dioxide-the main greenhouse gases, and the destruction of the ozone layer reduces the production of oH. The synergistic effect of OH eventually leads to the greenhouse effect.

$$N_2O + O(^1D) \rightarrow 2NO \tag{3}$$

$$NO + O_3 \rightarrow NO_2 + O_2 \tag{4}$$

$$NO_2 + h\nu \rightarrow NO + O \tag{5}$$

N2O reacts with the excited oxygen atomO(^{1}D) to form NO (reaction 3), and then NO reacts with O3 (reaction 4). The generated NO2 will decompose into NO and O (reaction 5) under the action of ultraviolet light, so that NO can be recycled, and a single N2O molecule can destroy a large amount of O3. At present, the contribution of N 2O to the destruction of the ozone layer has reached about 40 %, which is the main pollutant of ozone layer destruction in the 21st century (Liang, X., & Prinn, R. 2023)[8].

3.3.3. sulfate aerosol

SO2+OH->HOSO2->H2SO4.

Under normal conditions, SO2 reacts with OH to form sulfate aerosols, resulting in a cooling effect. However, anthropogenic emissions of CO and CH consumed OH, resulting in an increase in SO2 lifetime, a decrease in sulfate aerosols, and a weakening of the cooling effect.

In summary, the competitive reaction of methane (CH_4) and carbon monoxide (CO) emitted by human activities with hydroxyl radicals (OH) leads to a decrease in OH concentration in the atmosphere, which not only directly weakens the ability of the atmosphere to scavenge greenhouse gases, but also prolongs the life of warming gases such as methane, thereby enhancing its greenhouse effect. On the other hand, the reduction of OH breaks the equilibrium of ' cooling-warming gas ' -SO2 reacts with OH to form sulfate aerosol (with cooling effect), which is reduced due to the lack of OH, and the cooling effect is significantly weakened. At the same time, in the troposphere, the O3 precursor (such as CO) accumulates due to the blocking of OH scavenging, which accelerates the formation of O3, and its thermal insulation effect as a strong greenhouse gas is strengthened. In addition, the nitrogen cycle cascade reaction initiated by N2O in the stratosphere destroys the ozone layer by generating NO (a single N2O molecule can destroy a large amount of O3 through chain reaction), which weakens the shielding effect of the ozone layer on ultraviolet radiation. The cumulative increase of O3 in the troposphere forms a warming superposition effect. These three aspects of OH consumption effect and N2O chain reaction, SO2 cooling weakening effect are coupled with each other, and finally form a synergistic positive feedback of ' warming gas accumulation-cooling effect weakening-ozone layer loss ', which systematically amplifies the overall warming effect.

4. RESEARCH ON ECONOMIC COST INTEGRATION

4.1. Basic Introduction to CEI

The Cost-Effectiveness Index (CEI) is a quantitative tool used to measure the relationship between input costs and the results obtained. It aims to evaluate the efficiency and economy of resource input when achieving specific goals or outputs. By systematically analyzing costs and effects, and using mathematical thinking to present them in ratios or other quantitative forms, cost-effectiveness and cost-effectiveness analysis can help decision makers evaluate the advantages and disadvantages of different schemes or measures in resource utilization. In the medical field, for example, CEI can be used to compare the cost and health improvement effects of different treatment options; in the field of environmental protection, the relationship between the cost of different pollution control measures and pollutant emission reductions can be evaluated. It is also the angle from which this article wants to start.

A specific application of CEI is presented in the paper " Cost effectiveness analysis and ultra-low emission policy discussion of pollution reduction in coal-fired power plants. " The application of CEI is of great significance for studying the pollution reduction strategy of coal-fired power plants. When analyzing the pollution reduction of coal-fired power plants, the cost covers the expenditure on equipment purchase, operation and maintenance, energy consumption and so on. The effect is reflected in the emission reduction of various pollutants such as sulfur dioxide, nitrogen oxides and particulate matter. By calculating the CEI, we can clearly understand the cost of each unit of pollutant emission reduction when using different emission reduction technologies and measures. For example, comparing the installation of traditional desulfurization, denitrification and dust removal equipment with the use of advanced ultra-low emission technology, analyzing their cost differences under the same pollution reduction target, and using CEI to evaluate which scheme can achieve higher emission reduction effect at lower cost, so as to provide scientific basis for pollution reduction decision-making of power plants. Promote coal-fired power plants to find a balance between environmental protection and the economy (Dong, D., Jin, Y., & Zhang, S. 2016)[3].

Based on the above-mentioned cost-effectiveness analysis approach centered on CEI, this study, while adhering to the original starting point, further expands the analysis dimension from a newer perspective, that is, by examining the synergistic effects among chemicals for evaluation, aiming to provide a practical and novel method.

4.2. The specific application of CEI in solving the greenhouse effect - from the perspective of chemical synergistic effect

CEI = radiative forcing reduction (ΔRF)/life cycle emission reduction cost (C).

Radiative forcing refers to the disturbance of the earth 's energy balance due to changes in atmospheric components such as greenhouse gases and aerosols. The unit is Watt per square meter (W/m2). The positive value indicates that the disturbance will lead to the accumulation of surface energy, which is the direct physical mechanism driving global warming. Correspondingly, the reduction of radiative forcing (ΔRF) quantifies the extent to which this warming-driven effect is reduced by emission reduction measures such as controlling greenhouse gas emissions and regulating aerosol generation, and is a core indicator to measure the actual effect of emission reduction measures on mitigating global warming. Under the framework of the chemical mechanism focused in this study, the calculation of ΔRF needs to consider the synergistic effect of multiple gases. For example, as mentioned above, CO and CH4 form a coupling relationship by competitively consuming OH radicals, and N2O indirectly amplifies the greenhouse effect by destroying the ozone layer. Quantitative analysis of ΔRF should be included to accurately reflect the actual effect of emission reduction measures.

The whole life cycle emission reduction cost (C) covers the whole process economic input from the research and development of emission reduction technology, equipment purchase, operation and maintenance to waste treatment, including both direct hardware purchase cost and other indirect costs such as energy consumption and manpower input generated in the process of technology implementation. This refers to a comprehensive analysis of its effectiveness in order to comprehensively measure the resource costs paid to achieve the above-mentioned radiative forcing reduction.

The CEI value calculated by this formula essentially constructs the correlation between ' emission reduction effect-economic input ' : the higher the CEI value, the more significant the reduction of radiative forcing achieved by regulating atmospheric chemical processes such as enhancing the OH sink function by using the synergistic effect between gases and inhibiting greenhouse gas source emissions under unit cost, that is, the higher the efficiency of emission reduction schemes in balancing cost and temperature rise suppression effect. The core value of this indicator in this study is to help identify more efficient emission reduction strategies under specific chemical pathways by transforming complex gas synergy effects and source-sink interactions into comparable cost-benefit values, thus providing a scientific basis for balancing economic investment and climate governance goals.

4.3. Basic Methods Used by CEI for Assessment - Taking the coordinated Control of CO and CH4 emissions as an Example

Taking CO and CH4 emissions in the analysis of synergistic effects as specific examples, combined with the specific application of chemical synergistic effects of the two, the specific application method of CEI in the evaluation can be divided into four basic steps:

Firstly, the boundary between emission reduction plan and cost accounting is defined. Technical solutions such as industrial combustion system optimization schemes for simultaneous reduction of CO and CH4emissions in a specific area such as a plant are selected. The life cycle length (such as T years) is set, and the whole process cost (C) in the cycle is calculated, covering all relevant inputs, and the sum is recorded as C (unit: monetary unit, which can be adjusted according to the specific situation). Then the radiation forcing reduction (ΔRF) was quantified. Individual effect evaluation: For each gas emission reduction, the reduction effect of radiative forcing is calculated separately. If only CO (a % reduction) is reduced, the competitive consumption of OH radicals will be reduced, and the atmospheric lifetime of CH will be shortened. The reduction of radiative forcing caused by this effect is recorded as ΔRF1. If only CH 4is reduced (the reduction ratio is b %), the reduction of radiative forcing corresponding to the reduction of direct greenhouse effect is recorded as ΔRF2. Next, the synergy effect is integrated. Based on CO emission reduction, OH regeneration is promoted, CH4 degradation is accelerated, and additional radiative forcing reduction will be generated when combined emission reduction. At this time, the total radiative forcing reduction needs to consider the contribution value of the synergistic effect ΔRF3, and the calculation formula is: $\Delta RF = \Delta RF1 + \Delta RF3 - \Delta RF2$ (Note: the formula may need to be adjusted according to the actual situation, here is only an example, unit: W/m2). Among them, ΔRF3 is the additional effect of synergy. After completing these, the CEI value can be calculated, and the above ΔRF and C are substituted into the formula to obtain the CEI value of the synergistic emission reduction scheme:

$CEI = \Delta RF/C$

Finally, the scheme comparison and effectiveness judgment are carried out. In order to evaluate the cost-effectiveness of the synergistic scheme, we can choose only CH4 emission reduction as a reference for a single gas emission reduction scheme, and use the same method to calculate its CEI reference value (CEI '). Comparing the values of CEI and CEI ': if CEI is greater than CEI ', it means that under the unit cost, the synergistic scheme can achieve more significant radiative forcing reduction by virtue of the chemical synergistic effect of CO and CH4, such as strengthening the scavenging effect of OH radicals on CH_4, thus showing better cost-effectiveness. Conversely, it indicates that the economic efficiency of the collaborative solution is inferior to that of a single solution. This comparison provides a quantitative basis for screening efficient emission reduction strategies.

4.4. Reference Strategies for CEI

Based on the quantitative assessment results of CEI, a set of prioritized logic for selecting emission reduction strategies can be constructed. The core lies in achieving the optimal match between resource input and emission reduction benefits through the ranking of CEI values. As demonstrated in the research on the optimal selection of carbon emission reduction schemes for railway subgrade retaining walls, the optimal emission reduction scheme can be determined through LCA theory and sensitivity analysis methods. At the same time, referring to the research on the selection of China's carbon emission reduction paths and countermeasures, long-term carbon emission reduction plans should be formulated at the macro level, with clear goals and timetables, and the possibility of consumption energy emission reduction strategies and investment in green energy should be carefully considered.

Specifically, schemes with higher CEI values mean that each unit of cost input can bring about a more significant reduction in radiative forcing and should be included in the priority implementation sequence. Under the constraint of limited resources (such as human resources and funds), such schemes can quickly and effectively curb global warming. Especially when the schemes involve the utilization of chemical synergy effects among gases, their comprehensive benefits are often superior to those of single gas emission reduction. Therefore, they can be given priority in obtaining key resources such as technological research and development and policy support, thereby accelerating their implementation and promotion.

For schemes with a lower CEI value, the reduction effect corresponding to the unit cost is relatively limited. This might be due to insufficient technological maturity, such as a high error rate in some new greenhouse gas capture technologies leading to capital loss, or the lack of full exploitation of synergy effects. It could also be attributed to a high life-cycle cost, such as high equipment expenses. For such schemes, it is advisable to adopt a delayed implementation strategy and incorporate them into the long-term technology reserve and optimization system. By waiting for technological iterations to reduce costs and enhance efficiency, or in response to changes in scenarios, such as adjustments in regional emission structures or upgrades in global temperature control targets, the CEI value is expected to gradually improve over time. Once the technological maturity and economic viability reach the preset thresholds, they can be included in the implementation sequence. This approach not only avoids inefficient resource allocation but also ensures the dynamic adaptability of the emission reduction strategy.

In conclusion, when the derived CEI value is referred to as a policy implementation strategy, it takes into account both the pragmatic orientation of maximizing short-term benefits and the strategic perspective of long-term technological reserves and optimization. By dynamically adjusting the implementation pace of emission reduction plans, a sustainable balance between economic and environmental benefits can be achieved in global warming governance.

5. CONCLUSION

In summary, this paper conducts a systematic analysis centered on the core issue of global warming. It begins by delving into the key factors influencing global climate, identifying human activities as the primary driver of global warming, with the core impact path being the emission of greenhouse gases. Based on this conclusion, the paper further focuses on greenhouse gases for detailed research: on the one hand, it explains the mechanism by which greenhouse gases cause global warming, with a focus on gases such as carbon dioxide that have a significant impact on the climate. By exploring the balance between the "sources" and "sinks" of these gases, it reveals that since the industrialization era, the emissions from "sources" have sharply increased due to the rise in industrial and agricultural activities such as the burning of fossil fuels, while the absorption capacity of "sinks" has continuously weakened due to factors like deforestation. This imbalance has further exacerbated global warming. After clarifying the basic principle of greenhouse gases causing warming, the paper takes a chemical perspective, combining the chemical reaction characteristics of greenhouse gases, to deeply analyze the synergistic effects among gases in three typical scenarios, including the regulation mechanism of hydroxyl radicals, the cascading effect of the nitrogen cycle, and the influence of sulfate aerosols, laying a theoretical foundation for subsequent research. On this basis, the paper introduces the economic analysis tool CEI (defined as the ratio of the reduction in radiative forcing ΔRF to the full life cycle cost of emission reduction C), and incorporates the previously discussed synergistic effects into the calculation framework of ΔRF. Through examples of carbon monoxide and methane emissions, it elaborately demonstrates the application of CEI, concluding that "scenarios with synergistic reactions may produce a higher CEI than single reactions." Finally, based on the quantitative results of CEI, The paper proposes targeted emission reduction strategies: prioritize the implementation of measures with high CEI values, while measures with low CEI values can be postponed until the technology is mature. The research logic of this paper, from cause analysis to mechanism exploration, then to the application of economic tools and strategy proposal, forms a complete closed loop from understanding to addressing the issue of global warming, providing theoretical and methodological references for related emission reduction practices.

This study still has certain limitations: At the level of analyzing the chemical principles of global warming, although the mechanism of the synergy effect among gases has been explored, no quantitative simulation and verification have been conducted through model construction. Due to the research time and current knowledge reserves, the specificity and clarity of the related analysis still need to be enhanced. In the application part of the economic means CEI, only the basic research methods have been constructed and conceptually demonstrated. Due to the lack of systematic empirical data support, this is closely related to the scarcity of relevant cases and quantitative information in existing literature. Based on the above research limitations, future research can deepen exploration in the following directions: First, for the CEI assessment system, it is hoped that subsequent research will expand the sample range, refine the data collection dimensions, accumulate more systematic empirical data, form precise quantitative results covering different emission scenarios and different gas types, and promote the application of this means in the formulation of actual emission reduction policies and project evaluations, resulting in more replicable and scalable successful cases, thereby solidifying its theoretical basis and practical feasibility. Second, given the unique value of the chemical perspective in analyzing the interaction of greenhouse gases and revealing the micro-mechanism driving global warming, research in this field should be continuously deepened in terms of depth and breadth. In particular, it is recommended that the synergy effect among gases be taken into account when constructing and optimizing existing climate models, such as atmospheric circulation models and Earth system models. Through quantitative simulation and multi-scenario comparison, the contribution ratio and dynamic impact of the synergy effect on global warming should be analyzed to enhance the understanding of the chemical mechanism.

REFERENCES

[1] United Nations. (2015, December 12). Paris Agreement [Conference session]. 21st Conference of the Parties of the United Nations Framework Convention on Climate Change, Paris, France.

[2] Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., & Lenton, T. M. (2022). The risk of triggering irreversible climate tipping points significantly increases once global warming surpasses 1.5°C, as highlighted by recent studies.

[3] Dong, D., Jin, Y., & Zhang, S. (2016). Cost-Effectiveness Analysis of Pollution Reduction in Coal-Fired Power Plants and Discussion on Ultra-Low Emission Policies. China Environmental Science, 36(3),931–938.

[4] Houghton, J. (2004). Global warming: The complete briefing (3rd ed.). Cambridge University Press.

[5] Intergovernmental Panel on Climate Change. (2023). Climate change 2023: Synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[Core Writing Team, H. Lee and J. Romero (Eds.)]. IPCC.

[6] Liao, H., Ren, X., Ge, Q., et al. (2020). New Insights into Climate Warming and Its Sensitivity to CO_2 Concentration: Research Progress of the Climate Sensitivity Task Group in the CAS Strategic Priority Research Program "Climate Change: Carbon Budget and Related Issues". Science Bulletin, 65(27),2963–2974.

[7] Liao, M. (2021). Research on the Accumulation Effect of Greenhouse Gases in Ice-Sealed Reservoirs and Its Influencing Factors [Accumulation effect of greenhouse gases in ice-sealed reservoirs and its influencing factors] [Xi' an University of Technology].

[8] Liang, X., & Prinn, R. (2023). The growing role of nitrous oxide in stratospheric ozone destruction is becoming more significant as emissions from human activities, particularly agriculture and industry, continue to rise. SPARC Newsletter

[9] Zhang, J., Du, L., & Li, X. (2012). Who is the Main Cause of "Global Warming" —— A Review on Natural Gas Emission Sources, Geochemical Cycles, and Their Implications for Climate Change Origins. Journal of the Chinese Academy of Sciences, 27(2),226–233. https://doi.org/10.3969/j.issn.1000-3045.2012.02.012

[10] Li, G. C. (2005). Analysis of the Causes of Global Warming. Journal of Natural Disasters, 14(5),38-42.