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Views & Comments

Climate or Carbon Mitigation Engineering Management

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1. Introduction

Carbon mitigation engineering, also known as climate engineering internationally, is an umbrella term of engineering measures targeted at combating climate change and achieving carbon neutrality. Climate or mitigation engineering can be commonly divided into three categories based on technological principles [1]: ① carbon dioxide removal (CDR), which has the potential to achieve negative emissions by removing atmospheric carbon dioxide [2]; ② solar radiation management (SRM), which could limit temperature rises by increasing solar radiation reflection [3]; and ③ general geoengineering techniques, such as biochar and soil carbon sequestration, which are accessible means of improving the carbon absorption capabilities of natural ecosystems [4]. As the challenges of coping with climate change have intensified, climate or mitigation engineering has taken on a wider connotation. It now covers a considerably broader spectrum of engineering solutions and technical efforts for climate mitigation [5], such as renewable energy, energy efficiency technologies, carbon capture and utilization, and carbon sequestration.

Climate action has primarily focused on traditional emissions reduction and adaptation efforts over the last few decades [6]. However, empirical evidence has underscored the inadequacy of our responses to the climate crisis and heightened the urgency of this call to action. Our present emissions trajectory has left us on course for an average temperature rise of more than 3 °C above preindustrial levels by 2100, indicating a significant gap between current emissions and those needed to limit global warming to 1.5–2 °C, as set forth by the Paris Agreement [7]. Specifically speaking, the 2 °C target requires approximately 87% of mitigation scenarios to deploy negative emissions techniques, while the 1.5 °C target necessitates practically all emission trajectories to pursue negative emissions, in accordance with the net-zero emissions goal by the middle of this century [8,9].

With the worsening climate crisis, carbon mitigation engineering will undoubtedly be an essential component of the global climate governance framework. The urgency of global climate governance will not only encourage a large number of carbon mitigation engineering practice initiatives, but also inspire management circles to explore the theories of carbon mitigation engineering management (CEM).

2. Climate or mitigation engineering management

Climate or mitigation engineering—as opposed to general engineering—cuts across multiple industries and is large-scale, long-periodic, cross-regional, and fraught with uncertainty. Against this background, the success of mitigation engineering largely depends on scientific management. Built on technological innovation and other engineering and management experience, the practices of CEM have progressed in scale and effect. Nevertheless, theoretical research on CEM remains scattered, which will profoundly impact the wider spectrum of future practices in carbon mitigation engineering.

The latest research, which pinpointed the break-even point between mitigation costs and benefits under different global emission reduction strategies, has debunked the conventional wisdom that acting on climate change would result in losses [10]. This finding suggests that the scientific management of carbon mitigation engineering could not only ensure the Paris Agreement targets are met, but also provide a win–win situation for ecological improvement and economic development. However, the budding field of carbon mitigation engineering has been woefully controversial in its development, sparking a host of management concerns, such as collaborative management, social interaction, risk management, and intergenerational equity, among others. To address these issues, it is essential to provide systematic scientific advice and theoretical support for the practice of CEM, based on a summary of the existing engineering management theory and related discipline theory, as well as on carbon mitigation engineering's features and practical demands.

In short, the enormous complexities and risks connected with carbon mitigation engineering demand the establishment of new disciplines and theories to guide engineering development. The top priority for forging a new path ahead is to formulate a theoretical framework with ground-breaking and universal significance for CEM.

2.1. Characteristics of CEM

As an evolving field, CEM can be viewed as a subset of mega-engineering construction management. In this sense, the theories

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of CEM share four fundamental similarities with the theoretical system of mega-engineering management [5,11]:

(1) **The system operates on a massive scale.** Carbon mitigation engineering, once developed, will evolve into a new and more complex human-made system that is in constant interaction with the external environment. The system will comprise a natural interconnection of resources and elements, such as management, engineering, and technology, as well as transdisciplinary knowledge, such as natural science and management science, on a broader scale than ever before.

(2) **The elements are inextricably linked.** Because carbon mitigation engineering engages in complicated natural and social environments, it is influenced by a variety of constituent parts. For this reason, meteorological elements, economic factors, social imperatives, political concerns, and engineering management aspects are inextricably intertwined in CEM.

(3) **The endeavor is fraught with uncertainties.** There are three primary sources of great uncertainty in CEM. The first difficulty lies in determining the natural variability of climate change projections. The second source of uncertainty is the unpredictability of the social and economic development trajectory due to population, economic development, technological progress, and political slant. The final uncertain point is that several fundamental physical feedback processes and their scientific mechanisms are still poorly understood. These uncertainties demand the development of new CEM theories and insights based on traditional ways of dealing with uncertainty in order to reduce the degree of uncertainty and provide support for scientific modeling and effective management.

(4) **CEM scenarios have a high degree of unpredictability.** These scenarios describe the development vision, evolution law, and all conceivable paths of the composite carbon mitigation engineering system. Given the uncertainties described above, it is challenging to correctly predict the evolution of socioeconomic and physical systems, and it is even more challenging to clarify and quantify the feedback mechanism between the two systems.

Below, we outline the distinctive features of five aspects of CEM through a synthesis of its unique phenomena and principles [5,12].

(1) **Multiple entities are involved.** Climate change is a defining crisis that requires global solutions. The management and practice of carbon mitigation engineering will comprise a scientific system that evolves from the global governance framework. The entities of CEM will encompass almost 200 countries and regions around the world, each of which is at a distinct level of development, posing greater challenges to CEM.

(2) **High demand for synergy management.** The implementation of carbon mitigation engineering demands good coordination and interconnection among different industries, including steel, cement, electricity, chemicals, transportation, construction, agriculture, land use, marine ecology, and others. Pollution control should be focused on all types of greenhouse gases (GHGs), with CO_2 being the most essential, but also on methane (CH_4) and nitrous oxide (N_2O), among others. To achieve this, CEM needs to conduct cross-sectoral integration and collaborative pollutant-emission management across the whole life cycle of the pollutants.

(3) **A broad technical spectrum.** Different industries vary in their production processes, response processes, engineering site selection, and applicable technology. In coping with climate change, CEM necessitates a focus on the technical disparities among industries and departments and on the spatiotemporal feasibility of such industries and departments achieving integration and management.

(4) **Unprecedented risks.** Carbon mitigation engineering entails a diverse set of fields, a large system scale, a tight construction cycle, significant uncertainty, and limited public perception. Therefore, the risks in the design, implementation, operation, and management of carbon mitigation engineering are characterized by their grand scale, wide sources, diversification, multi-temporality, multiple scales, and high complexity. More importantly, some carbon mitigation engineering (e.g., nuclear power generation) may result in catastrophic and fatal safety risks if damaged or disrupted.

(5) **Difficulty in determining the best solution on a global scale.** Climate change is a long-term course. Based on the above characteristics, CEM should balance the development demands and carbon mitigation targets of different levels (system, engineering, project, technology, etc.), different time domains (centennial scale, intergenerational conflict, interannual change, engineering cycle, etc.), and different spatial criteria (globe, region, nation, city/county, etc.) in order to carry out the global optimization and systematic deployment of carbon mitigation engineering measures for another hundred years or even longer.

2.2. Key problems in CEM

CEM is a new interdisciplinary field that systematically studies carbon mitigation engineering and achieves global optimal control of carbon emission trajectories by utilizing planning, organizing, controlling, and other management methodologies. Here, we start with a quick rundown of five major management issues in CEM.

(1) **How much reduction in emissions is required?** So far, scientists are still divided over the worldwide emission-cutting capability of carbon mitigation engineering and the emission reductions required to meet global climate targets. Because the levels of emissions that are permissible while still achieving global temperature control are unclear, the transmission mechanism of "technologies → economies → CO_2 emissions → CO_2 concentrations → temperature increase → climate-related losses" has yet to be clarified, making it difficult to objectively quantify the number of emission reductions required for global climate governance.

(2) **Who will be responsible for reducing emissions?** The basis for resolving this question lies in determining which engineering options are available and how countries share responsibility for lowering emissions. The engineering capacity and resource endowments of various emission reduction entities differ substantially, due to the cross-regional and cross-sectoral character of climate change, which makes the assignment of emission-reduction responsibility across organizations a considerable challenge. As a result, eligible candidates—as well as the sharing mechanism of responsibility—must be further specified.

(3) **What is the appropriate schedule for implementing carbon mitigation engineering?** Due to the long-periodic nature of climate change, it is extremely difficult to understand the critical timing for carbon mitigation engineering deployment. It has proved difficult to strike a balance between contemporary benefits and the welfare of future generations. As a result, developing a global-optimal CEM implementation strategy is critical for the long-term viability of carbon mitigation engineering, as it will aid in achieving intergenerational equity and establishing a reasonable timetable.

(4) **How should carbon mitigation engineering be implemented most effectively?** The available knowledge of the technology paths and engineering planning that can be undertaken to satisfy the needs of climate governance is limited. Carbon mitigation engineering is distinguished by the fact that it encompasses multiple departments, different technology options, and unpredictably high costs, making future carbon mitigation engineering technology roadmaps difficult to anticipate. In this sense, the complexity degradation of the system should be emphasized in order to provide a well-organized layout for carbon mitigation engineering with a specific direction.

(5) **How can the effects and risks of carbon mitigation engineering be scientifically assessed?** A thorough understanding of the risks associated with carbon mitigation engineering can considerably improve exposure management techniques. Aside from planning, organization, scheduling, and technical management, it is essential to weigh the costs, benefits, and risks of various carbon mitigation engineering alternatives. From this standpoint, risk management should be incorporated as a key part of CEM.

These management concerns, simply stated, hint at the need for more standardized planning management, organization management, progress management, technical management, and risk management in CEM.

3. The Time–Space–System Synergy Theory of CEM

Based on a systematic perspective of scientific development, we propose the Time–Space–System Synergy Theory of CEM (Fig. 1). This theory, which strives to synergize the time domain, spatial criteria, and system elements, has three distinctive management features.

In terms of time synergy, we suggest a management coordination mechanism featuring a time axis that drives the optimization of carbon mitigation scheduling. The cornerstone of prioritizing carbon mitigation engineering deployment and critical time nodes is intergenerational equality. Carbon mitigation engineering should embrace a dynamic pattern of incremental evolution and iterative improvement in order to explore a globally optimal solution in pursuit of scientific methodology. As a result, the best timing and effort to reduce emissions in line with different climate targets—as well as carbon neutrality goals—can be determined, ensuring both short-term and long-term coordination and intergenerational fairness.

In terms of space synergy, a management operating mechanism that features interconnected entities and hierarchical integration can be gradually shaped in order to holistically coordinate the global and local relationships. This mechanism highlights the significance of organizational management in achieving cross-regional all-win harmony. Accordingly, the hierarchical integration of management, engineering, and technology across various countries can be realized by articulating the management objects and responsibility sharing of CEM.

In terms of system synergy, we recommend a management and control system with five dimensions, coupled with a closed-loop feature with controllable integrity. This system is capable of effectively coordinating the five-dimensional development goals of economic transition, technical innovation, energy revolution, emissions control, and climate governance. The best allocation and effective integration of resources and elements can be realized by setting emission-reduction targets, making engineering proposals, assessing risk impact, upgrading process design, and organizing numerous entities. Consequently, collaborative control of economic development and emission reductions—as well as comprehensive optimization of multiple systems—can be achieved.

As indicated above, this synergy theory would aid in the sound development of engineering technology in accordance with various management objectives while still considering the sequence of emission-reduction efforts, the demand balance of various micro-entities, and well-balanced macro systems. In brief, CEM revolves around management innovation in the areas of conduct, planning, organization, process, technology, and risk management, with the goal of answering five essential questions: How much must be reduced, how will it be reduced, who should contribute, when must it be reduced, and what effect will it have?

A range of carbon mitigation engineering and technology management studies are putting the Time–Space–System Synergy Theory into practice. Two published studies are presented here to help explain how this theory can be applied. The first study aimed to apply the synergy theory to address the key scientific issue of how to reconcile short-term economic losses with long-term climate threats on temporal and geographical scales. To achieve global climate governance, the Paris Agreement established a dynamic mechanism requiring the ratified parties to update their nationally determined contributions (NDCs) on a regular basis [13].

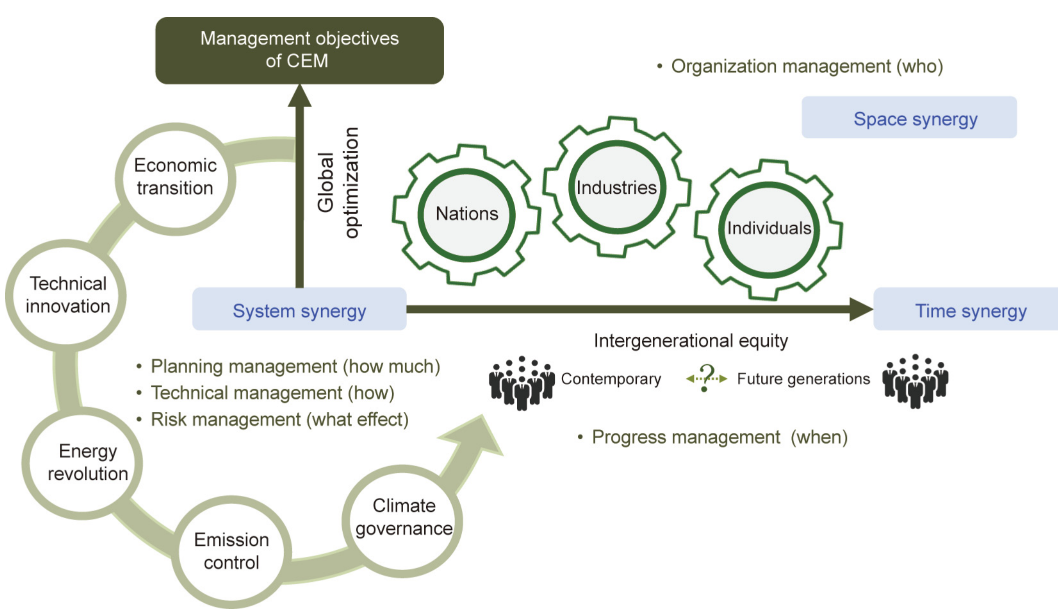

Fig. 1. Schematic diagram of the Time–Space–System Synergy Theory of CEM. Time synergy here is performed to balance short- and long-term priorities in order to determine when emissions must be reduced and to achieve intergenerational equity. To answer the question of who should contribute, spatial synergy is applied to coordinate the global and local relationships in their entirety, as well as to determine the most equitable and cost-effective emission reduction responsibility sharing scheme. System synergy is capable of coordinating five-dimensional development goals, balancing the relationship between these goals and emission reductions, and attaining holistic optimization of multi-system emission reductions. This enables us to answer the other three crucial CEM questions: How much must be reduced, how will it be reduced, and what effect will it have?

Unfortunately, current scientific evidence indicates that there is a significant emissions gap between current NDCs and the 2 °C goal [14,15]. More worryingly, some governments are solely interested in short-term economic growth and are unwilling to improve emission-reduction initiatives. However, unless major steps are taken to combat climate change, the world is likely to face bigger threats. With such a puzzling quandary, it is necessary to perform research on approaches to global climate governance targets in the post-Paris Agreement era. Based on the theory presented in this research, Wei et al. [10] developed the China's Climate Change Integrated Assessment Model (C^3IAM) to explore various countries' self-protection strategies under the uncertainty of climate damage and carbon mitigation engineering technologies. From a pool of more than 100 strategies, nine strategies were finally highlighted to reduce emissions beyond the current NDC target. These nine self-protection strategies can assist each country in achieving higher net incomes and maximum benefits in comparison with its current NDCs, while also meeting the 2 °C target. In addition, the study provides plans for further emission reductions in 134 major countries around the world in order to achieve 2 and 1.5 °C by 2100, including regional, national, and grid-scale improvement initiatives in various timeframes. The findings of this study, supported by the synergy theory of CEM, reveal the global break-even threshold (2065–2070) for combating climate change and disprove the notion that climate change actions will have negative effects on the global economy. Thus, this study provides a scientific foundation for international cooperation in the face of long-term climate change.

Another study set its sights on an important type of carbon mitigation engineering: carbon dioxide capture, utilization, and storage (CCUS). The key challenges that are currently impeding large-scale CCUS development are: ① the identification of carbon sources that meet the requirements of global CCUS implementation; ② a consistent and comparable evaluation of CO_2 storage potential; and ③ the overall source-sink matching of large-scale CCUS implementation. To fill these gaps in previous research, Wei et al. [16] created a 1 km × 1 km global carbon emission grid database with integrated data on geographic information, industry emissions, and land-use type, and identified 4220 eligible carbon clusters. The CO_2 storage potential of 794 major onshore basins around the world was then calculated using a unified framework. Based on the synergy theory, a cluster-based source-sink matching optimization model (C^3IAM/GCOP) was built in order to scientifically propose a global CCUS deployment strategy to achieve the 2 °C goal. According to the analysis, the global low-cost deployment of CCUS necessitates the participation of 85 countries or regions. The majority of CCUS engineering will be spread in China, the United States, the European Union, Russia, India, and other countries and regions.

The two studies described here demonstrate how CEM synergy theory may be used to perform CEM research across chronological, geographical, technological, economic, and social dimensions. Based on particular management objectives, the theory can offer insights on who, when, where, and what type of climate engineering might be expected, as well as on how it can possibly be implemented.

4. Prospects and suggestions

CEM, as an emerging field, is gradually maturing. It presents a way for us to take full advantage of management tools to steer climate or mitigation engineering in a scientific manner, as well as to cultivate a systematic viewpoint on the value of carbon mitigation engineering.

In conjunction with carbon mitigation engineering practice, we must continue to ponder appropriate theoretical origins for future CEM toward coordination mechanisms, risk mitigation, business strategy, technology selection, and climate justice, among others. There is also a strong call for the establishment of an integrated tripartite appraisal system for carbon mitigation engineering in order to allow its incorporation into the global governance structure. Perhaps more crucially, as reflected in the concept of climate ethical development, the public needs to be more aware of the potential benefits of carbon mitigation engineering implementation and management.

In addition, we could promote CEM in all areas by drawing upon the experience that has been gained at key points. By fostering global carbon mitigation engineering demonstration projects, the theoretical foundation of CEM will undoubtedly be updated on a regular basis. Moreover, in order to increase the theoretical system's universality, we earnestly encourage climate-vulnerable countries to actively participate in the CEM dialogue and decision-making process. Against this background, a theoretical CEM system can be developed, with engineering capability as the foundation, climate equity as the orientation, risk prevention as the major vein, engineering sustainability as the destination, and multi-agent collaboration as the core.

Finally, we encourage more scholars to get involved in CEM research. Although this study has provided a systematic theoretical framework for CEM, it is mainly from the standpoint of management, making it impossible to address all of the issues that arise in CEM—particularly potential concerns at the moral and geopolitical levels [17–19]. Due to the global characteristics of climate change, for example, the use of carbon mitigation engineering technology, or CEM, in one country would result in climate damage being transferred to neighboring regions or free-riding in international CEM. This may further lead to international disputes over climate mitigation responsibilities. In order to solve the various possible risks of CEM and promote the widespread deployment of carbon mitigation engineering around the world, scholars from multiple disciplines need to work together to promote the development of CEM disciplines through more academic research and management practices.

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