Role of natural gas hydrate in regulating the global energy and carbon cycle

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Received: January 31, 2024; Accepted: June 5, 2024; Published Online: June 6, 2024; https://doi.org/10.59717/j.xinn-energy.2024.100031

Citation: Kou X., Li X., and Wang Y. (2024). Role of natural gas hydrate in regulating the global energy and carbon cycle. The Innovation Energy **1(3)**: 100031.

Natural gas hydrate (NGH) represents a significant reservoir of carbon with immense potential as an energy source. However, the precise role of NGH in regulating the global energy distribution and carbon cycle pattern remains controversial. We aim to propose a new research framework that integrates the implications of NGH as an agent within various complex adaptive systems, ranging from the molecular-scale statistical thermodynamic system to the large-scale cold seep ecosystem, as illustrated in Figure 1. By examining the carbon cycling dynamics in relation to NGH exploitation and management strategies, a comprehensive understanding of its multifaceted role can be developed. With this conceptual framework, we can gain valuable insights into both the opportunities and challenges associated with hydrate-related research. Finally, the principle of 'acting locally and thinking globally' is proposed for future NGH exploitation and management.

ENERGY AND CARBON CYCLE IN COMPLEX ADAPTIVE SYSTEMS

The exploitation of energy resources is an inevitable trend for social development, and the resources extracted from our planet play crucial roles in climate regulation. The gap between resource exploitation and environmental protection can be characterized as 'acting locally and affecting globally' (Figure. 1). Local behaviors related to natural resource exploitation manifest globally through climate change, which can shift the balance of energy distribution through energy structure regulation or policy intervention. The hidden problems behind the contradiction between energy development and environmental protection are particularly tough to address since the underlying energy and environmental systems are complex adaptive systems (CAS). The concept of complex adaptive systems (CAS) was pioneered at the Santa Fe Institute. CAS represents a framework for studying the dynamics of complex systems composed of multiple adaptive agents. It has been widely applied in various areas such as economics, biology, chemistry and linguistics, etc. In CAS, agents are individual entities capable of adaptive behaviors, competition, cooperation, and evolution, collectively shaping the systems' behaviors.

ROLE OF NATURAL GAS HYDRATE IN COMPLEX ADAPTIVE SYSTEMS

Natural Gas Hydrate (NGH) is a solid, ice-like compound composed of water molecules and natural gas, typically methane. NGH deposits are found in marine sediments and permafrost regions worldwide. The exchange of energy between NGH and its surroundings through the phase transition stimulates the self-adaptive, proactive, and dynamic characteristics of NGH, making it an essential agent within diverse CAS. These NGH related processes have significant effects on the CAS system, including changes in sediment stability, geo-mechanical properties, and risks of greenhouse gas emissions. In the South China Sea, the NGH reserves hold about 8.5×10^{13} m^3, which is equivalent to 2.12 times the total conventional natural gas resources found on land. These reserves interact with multiple CAS such as energy-economy systems and climate-ecosystems, thereby influencing global energy supply and climate change dynamics.[1] Additionally, NGH is closely related to the behaviors of exploitation, carbon storage and utilization, symbiosis with microorganisms, and the fragile ecology of cold seeps under deep marine conditions, complicating the interactive patterns within CAS which involves various agents such as marine animals, plants, and organisms.

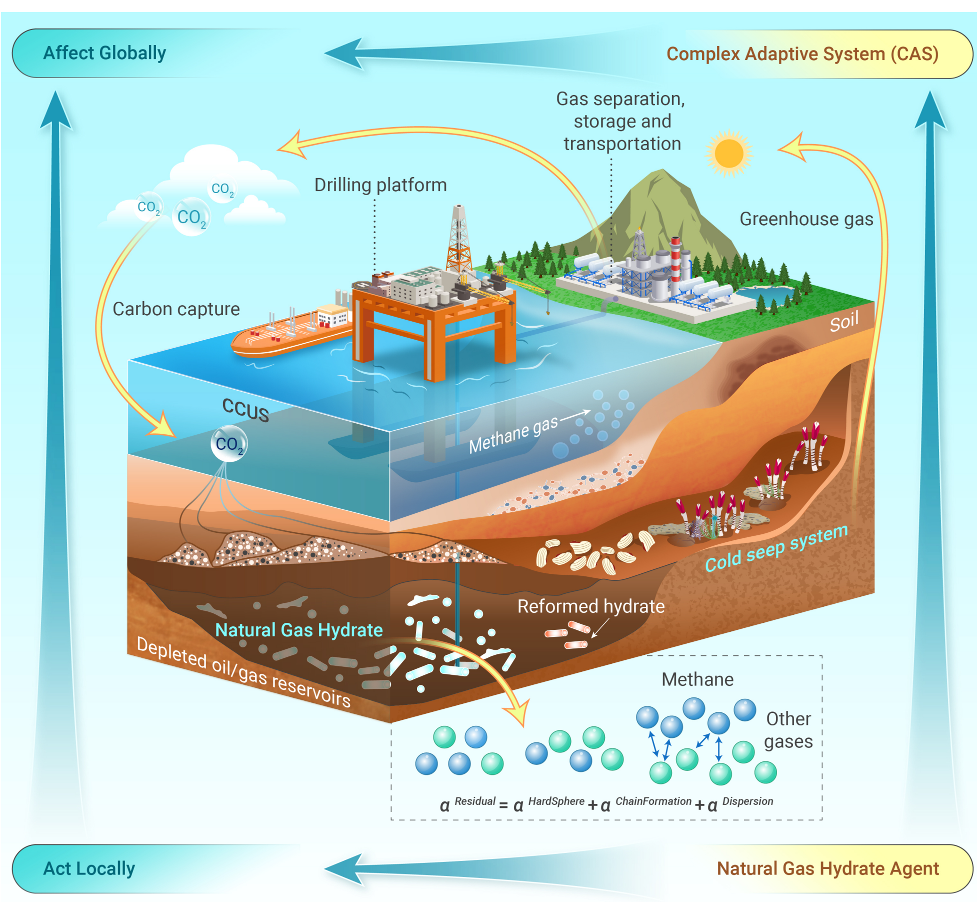

Figure 1. Conceptual model of the natural gas hydrate as an adaptive agent in multiple Complex Adaptive Systems (CAS).

The NGH exploitation strategy without considering the CAS might lead to undesirable ecological consequences. It is imperative to adopt an integrated approach through interdisciplinary research and international collaboration to understand the essential features and roles of NGH as an agent within multiple CAS. To achieve this, the development of a basic conceptual framework that reveals the multifaceted role of NGH becomes necessary. Figure 1 presents a conceptual framework that explores the agent role of NGH across various scales of CAS, from the basic molecular thermodynamic system to the complex marine cold seep system. The molecular thermodynamic system establishes foundational principles that governs the preservation or destabilization of NGH under different environmental conditions. The marine cold seep system emphasizes the interactive behaviors among NGH and other adaptive agents in deep ocean.

TYPICAL CAS: FROM THE PERSPECTIVE OF MOLECULAR THERMODYMAICS

In the molecular thermodynamic system, inter-molecular forces determine the physical properties and chemical equilibrium conditions of NGH. These forces depend on the ‘surrounding information’, such as molecular components, temperature, pressure, and environmental conditions. The interaction of methane gas with other gases or solvents can be described by the Statistical Associating Fluid Theory (SAFT) EoS.[2] Derived from Wertheim's theory of Helmholtz energy expansion, the SAFT EoS is termed as the residual Helmholtz energy (ΔA), which includes the hard-sphere repulsive forces, chain formation, association, and dispersion terms. The gas and liquid components act as agents within this molecular-scale CAS, and NGH represents the assembled outcome of interactions among these agents. The SAFT EoS can be used to determine phase equilibria under various gas and liquid component conditions. When applied to more complex real-world scenarios, such as deep-sea environments, various adaptive agents including macro and micro-organisms, and the interaction forces among them should be incorporated into the SAFT EoS. For example, biofilms and inner pores of shells or sediments serve as nucleation sites for hydrate formation. Significantly, the effects of surface properties of these biofilms (dependent on hydroxyl and carboxyl functional groups) on hydrate formation equilibrium conditions should be incorporated into the SAFT EoS by introducing a new term representing capillary forces. Additionally, the SAFT EoS proves valuable in carbon capture, utilization, and storage (CCUS) technologies by predicting the volumetric properties of liquid carbon and carbon dioxide hydrates in pipelines or deep-sea environments. Therefore, understanding how to enhance the adaptability of NGH under different environmental conditions, such as deep marine environments, permafrost regions, and gas/oil pipelines, from a thermodynamic perspective is important for the development of hydrate exploitation and hydrate-based industrial applications.

TYPICAL CAS: FROM THE PERSPECTIVE OF MARINE COLD SEEP

Within the cold seep complex adaptive system (CAS), NGH plays the role of an agent that regulates the release or preservation of methane gas while interacting with local ecosystems. The adaptability of the NGH agent to the environment is driven by both internal and external forces within the cold seep CAS. Internally, the sea level affected by climate change leads to temperature or pressure variations beyond the equilibrium condition of NGH, resulting in a large amount of hydrate decomposition.[3] The unpredictable process of NGH decomposition makes it challenging to forecast the feedback loop of the carbon cycle between ocean and atmosphere. Additionally, the hydrate decomposition not only accelerates the release of methane gas but can also generate new pores and fractures in the sediments. The released methane gas would migrate through pores and fractures to shallower sediment layers. The changes in methane flux within the shallow sediments are found to synchronize with the microbial community responses,[4] sustaining the rich ecosystem on the seabed and assisting in the synthesis of bio-medically significant compounds.[5] Externally, anthropogenic perturbations (such as resource exploitation or CCUS, as shown in Figure 1) would exacerbate the complexity of the CAS by providing instantaneous energy inputs that would otherwise require prolonged geological evolution. This influx of energy shifts the system boundaries by affecting sea level, sea temperature, and sedimentation rate. This may further induce significant consequences such as flooding in coastal areas, diffusion of greenhouse gases, and the spread of infectious diseases. Furthermore, resource exploitation presents additional economic effects, including changes in plant productivity, loss of inshore real estate, and regional unemployment. These economic impacts should also be considered when evaluating the consequences of resource exploitation. Therefore, the proposed NGH exploitation strategy within the cold seep CAS should consider scientific, economic, and ecological issues mentioned above.

FUTURE PERSPETIVES TOWARDS NATURAL GAS HYDRATE

The evolution of NGH and its interactions with ecosystems play a dominant role in the global carbon cycle. The technological solutions aimed at mitigating greenhouse gas emissions from anthropogenic activities involve capturing and utilizing the gas through effective methods and reducing dependency on carbon-based fossil fuel resources. These efforts necessitate urgent industrial utilization and resource development of NGH. However, it is noteworthy that addressing energy and environmental challenges requires international and interdisciplinary cooperation across regions. Several prospective advices for future NGH research are provided: firstly, to improve the adaptivity of NGH in various application scenarios by enhancing interdisciplinary collaboration; secondly, to explore new marine niches that promote the co-evolution of resource development and environment protection under deep marine conditions; thirdly, to introduce a bottom-up approach to NGH exploitation by developing an agent-based model. In summary, adopting an “acting locally, thinking globally” approach is crucial. This involves conducting short-term local field testing and collecting feedback data, while engaging in long-term global monitoring and developing complex adaptive system models. These actions are necessary for the future exploitation and management of NGH.

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FUNDING AND ACKNOWLEDGMENTS

This work is supported by National Natural Science Foundation of China (52306286, 52122602, 52127815), China Postdoctoral Science Foundation (2022M723160), Guangdong Special Support Program Local innovation and entrepreneurship team project (2019BT02L278), Special Project for Marine Economy Development of Guangdong Province (GDNRC[2022]43, GDNRC[2022]45), and Fundamental Research & Applied Fundamental Research Major Project of Guangdong Province (2019B030302004, 2020B0301030003), which are gratefully acknowledged. The funders had no role in study design, data collection and analysis, decision to publish or preparation of the manuscript.

DECLARATION OF INTERESTS

Xiao-Sen Li is an Editorial Board member of The Innovation Energy and was blinded from reviewing or making final decisions on the manuscript. Peer review was handled independently of this member and their research group. The other authors declare no conflicts of interest.