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A Co-Creative Approach for the Commercialization of Offshore Methane Hydrate Resources

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Abstract. The MH21-S R&D consortium (MH21-S) established in 2019 advances technological development toward the commercialization of Japan's offshore methane hydrate resources. This research is conducted as a part of MH21-S, funded by the Ministry of Economy, Trade, and Industry. Under the global trend toward decarbonization, there is a strong demand to combine methane hydrate production with CCS (carbon dioxide capture & storage) technology. Among the various possible combinations, we need to define the target architecture and develop strategic plans for it. However, the uncertainty and complexity of the socio-technical system make it challenging to derive a consensual decision. In this paper, we propose a co-creative approach engaging various stakeholders through workshops and model-based discussion. The workshop was designed to gather ideas from stakeholders from various backgrounds. The ideas raised in the workshops were analyzed to construct a morphological matrix to generate a comprehensive solution space. A simulation model was developed to quantitatively evaluate the wide variety of concepts, by integrating several element models, such as economic evaluations models, gas production models, and production system models. The model interface was designed to support the understanding of the complex system. Through the demonstration of this approach, we have developed a model that can provide quantified evaluations of concepts that support the consensual decision-making of the target architecture.

Keywords. Decision Support, Co-creation, Methane Hydrate, Ocean Development

Introduction

Fuel prices are soaring due to the rising global demand for energy. Moreover, from the viewpoint of the security risk in Japan, where natural resources are scarce, there is a need to develop new domestic energy resources, and methane hydrate is considered a potential energy resource. The MH21-S R&D consortium (MH21-S) established in 2019 advances technological development toward the commercialization of Japan's offshore methane hydrate resources.

However, the project is not making sufficient progress toward the "private-sector-led project for commercialization to be launched in the latter half of the 2020's" [1] as stated by the Ministry of Economy, Trade, and Industry, as it is necessary to continue

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demonstrating continuous gas production. Moreover, there is a solid demand to combine methane hydrate production with CCS (carbon dioxide capture & storage) technology under the global trend toward decarbonization.

There are several issues that need to be addressed to achieve the desired state of commercialization. First of all, multiple evaluation criteria defined by various stakeholders must be valid besides economic evaluation. In addition, for an unprecedented developing system, solution space to be searched is vast due to technological seeds and their combinations. The developing system is enormous and complex, so it is not easy to evaluate its concept.

Then, we need to define the target architecture and develop strategic plans for it to derive a consensual decision among the various stakeholders. In particular, Japan has a hierarchical society and consensus decision-making structure, and there is a need for the transparency and completeness of the information[2]. However, information on methane hydrate development is fragmented and complex, and it is challenging to achieve transparent discussions among stakeholders.

On the other hand, a co-creative approach is considered to be effective among the stakeholders to proceed with the project[3] and this paper proposes a methodology for a co-creative approach engaging various stakeholders through workshops and model-based discussion. As its specific implementation, this paper aim to (1) design a process that allows stakeholders to participate in concept creation discussions and improve their understanding of the project and (2) use a simulation model to provide transparency and objectivity in the detailed evaluation of development concepts.

1. Previous research

One of the factors that make discussions difficult in methane hydrate development is that the methane hydrate production system consists of many subsystems and technologies, and the connections between them are not clear, so it is unclear what kind of architecture to target. Matsudaira et al.[4] used the systems approach method to build a system and solve the problem by looking at the whole system and systematically capturing the connections between each component. The subsystems that make up the system are listed in a formative manner, and all the concepts are created by combining the options of the subsystems. In the end, the concepts were compared and examined, and the promising concept was inferred from the perspective of economic efficiency and risk assessment, enabling the identification of technologies that should be developed with priority. Nakagawa[5] extended the subsystems that are decision-making items from Matsudaira's research and created a new concept proposal. It encompasses new possibilities by inferring the promising concept from a wider range of concept proposals. In the study by Matsudaira and Nakagawa, the systems approach method was introduced to select the basic design concept, and the possibility of rational selection was suggested from a model-based approach.

Further improvement of the model was conducted to account for uncertainty. The economic evaluation value should change fluidly depending on the production volume, gas price fluctuations, and development period, and it is considered to be an essential factor for decision making. Makino and Isogami[6,7] developed a subsystem model that incorporates probablistic evaluation of production volume and economic efficiency concerning the development time axis. In addition, the degree of variability was quantitatively evaluated by conducting Monte Carlo simulations of future uncertainty. In this model, the system boundary is the production and sales of natural gas from methane hydrate, and it covers the development concepts that do not take carbon neutrality into account.

2. Methodology

In this research, the research flow is divided into two main processes: the process of expanding candidate ideas and the process of narrowing down the development concepts. In the idea expansion process, in addition to the development concepts proposed by the MH21-S Strategic Commercialization Team, the search space for candidate development concepts is expanded by consolidating the knowledge and ideas of stakeholders through the workshop. In the process of narrowing down the development concepts, the concepts are quantitatively evaluated using a simulation model to enable strategic decision-making, and the promising development concepts are presented.

2.1. Process of idea expansion

In the process of idea expansion, our aims is to increase the number of ideas. In addition to idea generation, the process of idea expansion aims to bring transparency to the decision-making process among stakeholders. Two steps are taken in this process: system analysis of the proposed development concept and idea generation through a workshop with stakeholder participation.

In the system analysis, the methane hydrate development system processes are decomposed based on the development concept proposed by the MH21-S Strategic Commercialization Team. In addition, a morphological matrix is used to organize the ideas used in the system processes systematically[8]. The morphological matrix is a decision support tool that can systematically describe the decision items and the ideas in the decision items, and a new concept is generated by multiplying the ideas.

As the next step, a workshop is held with the participation of a wide range of stakeholders as the co-creative approach. In the workshop, new ideas are generated through brainstorming discussions starting from the proposed development concept and its ideas using the Bias Breaking Workshop method[9]. The generated ideas were embedded in the morphological matrix, and the extent to which the workshop expanded the search space was quantitatively measured. Then, the impact of the workshop is analyzed through a questionnaire to stakeholders—The questionnaire measure how the understanding of the stakeholders changed before and after the workshop.

2.2. Process of narrowing down the development concept

In the process of narrowing down the development concept, the objective is to make a strategic decision that considers all development concepts in the search space and judges rationally. When there is large uncertainty in the system, an optimal decision is not always defined. Thus, our aim is to reduce the ambiguity and complexity of the system using models, and make effective decisions under uncertainty, i.e. strategic decisions. Two steps are taken: development of a simulation model and selection of a development concept from simulation results.

The simulation model was developed to quantitatively evaluate the wide variety of concepts, by integrating several element models, such as economic evaluations models, gas production models, and production system models. This model sort out the complexity and uncertainty of large-scale methane hydrate development. In addition, by recombining the modularized system elements in the model, all development concepts in the search space are evaluated to analyze the technology seeds.

Finally, promising development concepts are estimated based on comparing multiple concept results from the model by developing a user interface for comparative study.

3. Results

3.1. System analysis

Currently, the development concept of Yamamoto et al.[10] is being discussed within the MH21-S Strategic Commercialization Team. The main methane hydrate development concept in consideration of carbon neutrality is as follows.

1. The natural gas produced is sent to onshore power generation facilities using pipelines and converted into energy carriers such as hydrogen, ammonia, and electricity. The CO2 generated in the process is stored underground or in coastal aquifers to achieve carbon neutrality.
2. The natural gas produced is converted into electricity at sea and transported to shore using submarine transmission cables. The CO2 generated is not transported but is directly sequestered in the deep seafloor (aquifers and methane hydrate-bearing layers).
3. The energy is converted to hydrogen and ammonia at sea. The discharged CO2 is not transported but is directly sequestered in the deep seafloor (aquifers and methane hydrate-bearing layers). Pipelines or shuttle tankers are assumed to be used for transportation to shore.

Based on these development concepts, the methane hydrate development processes include: mining and production process to produce natural gas from methane hydrates under the seafloor; the conversion process to convert natural gas into other energy carriers such as hydrogen and ammonia; the transportation process to transport the gas from offshore to onshore; and the sequestration process to sequester the emitted carbon dioxide.

Next, based on the decomposed process, the ideas that are the components of the methane hydrate development concept are analyzed and systematically organized into a morphological matrix. The concept is determined by selecting the ideas listed on the right side of the decision items one by one as options. The morphological matrix of the proposed methane hydrate development system is shown in the table.

Table 1. A morphological matrix in the proposed development concepts.

Process	Decision item	Ideas
mining and production	production system	Platform / Long tie-back system
conversion	Energy carrier	Electricity/Hydrogen/Ammonia
	conversion site	Onshore/offshore
transportation	transportation target	Electricity/Hydrogen/Ammonia/Natural gas
	transport method	Pipeline/Shuttle tanker/Cable
sequestration	CCS location	Underground /Seafloor

The constraints of the morphological matrix in Table 1 are as follows.

1. When the long tie-back system is selected in the production system, the conversion site is onshore, the transportation target is natural gas, and the transportation method is the pipeline.
2. When the conversion site is onshore, the transportation target is selected as natural gas.
3. If the conversion site is offshore, the target is the same as the selected energy carrier.
4. If the target is electricity, the transmission line is selected as the transport method.

28 development concepts can be logically considered by combining the options.

3.2. Workshop

A total of three workshops were conducted. The first workshop was held for six students. The second workshop was for MH21-S professionals, with 30 participants. The third workshop was attended by a broader range of 24 experts, including government officials and professors from other fields.

As for the schedule for the day, we conducted a 3-hour online workshop.

1. In the preliminary briefing, participants are were given an overview of the workshop. The purpose of the workshop and the currently proposed development concept were explained, and the participants were asked to list what can be interpreted as bias.
2. Next, in the first work in the workshop, we divided into teams of four to five people and used Apisnote, an electronic sticky note web tool that can be used in the cloud, to describe biases in the cloud and discuss biases. We discuss the cause of each bias and the effectiveness of breaking the bias to create a foundation for idea generation.
3. The second work is to create new ideas and concepts based on the described biases. The concept, which is an overview of the entire system, and the idea, which is a more detailed item, are recorded on Apisnote. It is said that the method of generating ideas through individual work is more creative than brainstorming ideas through team discussions[11]. Therefore, in this workshop, the participants worked individually to generate concepts and ideas.
4. In the third work, the team members explain the concepts and ideas generated and discuss them within the team. The team aims to create synergy from the ideas proposed by other team members and create new ideas through discussion.
5. After all the work is completed, present the ideas that were considered promising within all the teams and share what initiatives and discussions took place among the teams.

A total of 117 ideas and comments were collected in the Bias Breaking Workshop. To quantitatively evaluate the increase of ideas, these ideas were organized into a morphological matrix by dividing them into three levels of hierarchical structure: "social significance of methane hydrate," "commercialization concept at the time of commercialization," and "technological system." In the system analysis, there were six decision items in the morphological matrix and 16 options for them. The results of the workshop showed that there were 30 decision items, and the total number of these options increased to 82 (Table 2).

Table 2. Example of morphological matrix results in the technological system

Black-figure show the system analyses results and red-figure show new ideas generated in the workshop

Decision item	Ideas
Well equipment	Moving equipment/ Installing equipment
Production system	Platform / Long tie-back system
Production continuity	Continuous and stable production/ Intermittent production
System management	The remote system/ The fully automated system
Produced water from hydrate	Utilizing/ Discharging

In addition, we conducted a questionnaire on the level of understanding among the participants to quantitatively measure whether the workshop functioned as part of a co-creative approach. The questionnaire allowed the participants to rate their level of understanding on a scale of 1 to 5 before and after the workshop, and an average score of 3.85 was obtained from 40 participants.

3.3. Development of a simulation model

This section constructs a simulation model that manages the uncertainty and complexity of the methane hydrate development system.

Since the simulation models did not consider the calculation of carbon neutrality in Makino and Isogami's previous research, we extend this model to evaluate development concepts that consider carbon neutrality[6,7]. The 28 development concepts proposed by the MH21-S Strategic Commercialization Team are subject to evaluation, and each idea summarized in Table 1 was incorporated into the model as calculation formulas and data. The evaluation values are economic efficiency and energy return on investment(EROI) in this paper, and the models calculate each concept.

The simulation models consist of two main parts: a system model to estimate energy production and an economic model to estimate revenue and price changes. In the system model, the model was subdivided into the production, energy conversion, transportation, and CCUS models to manage the complexity of the system. The development was needed on the transportation model, the conversion model, and the CCUS model, where information was particularly lacking.

However, since there are many uncertainties and unprecedented technology development evaluations and it is challenging to evaluate absolute values, this study organizes the information based on the published literature. The numerical data used in the model establish the relative figures among the energy carriers. An example of the capital cost estimation of a liquefaction plant, the relative cost of each energy carrier is calculated based on the capital cost of hydrogen under severe liquefaction conditions (Table 3).

Table 3. Capital cost for each component (Unit: million $)

Set the value relative to the orange value.

	Platform	Compressor	Pipeline	Liquefaction Plant	Shuttle tunker	Storage tank
Gas	87	15	42	100	31	45
Hydrogen	87	20	69	114	54	45
Ammonia	87	29	55	35	23	45

In addition, since unknown uncertainties need to be clarified and managed as known uncertainties, uncertainty is organized within the model[12]. The uncertainties that are dealt with within the model are mainly assumed to be methane hydrate production volume, market price fluctuations, and technological development. In this model, uncertainty is included in the calculation of each model and the output results are different for each calculation. Monte Carlo simulation is introduced to express how the uncertainty of each element propagates to the entire system.

The model interface was designed to support the understanding of the complex system. Additionally, since preconditions to be calculated in the model are different for each user, the numerical figures such as field data and energy price are set from the interface as parameters. Therefore, even if the same development concept is evaluated, the output result is the prediction result based on the user.

3.4. Selecting a promising development concept

This section aims to estimate promising development concepts based on a comparison of multiple concept results from the model. Since this research mainly focused on developing the transport and conversion models, we estimate the promising energy carriers such as hydrogen and ammonia from methane hydrates.

The Assumptions of calculation such as the production capacity of wells and development years are set as shown in Table 4 below based on the information provided by the MH21-S[13]. The Basic Hydrogen Strategy was enacted by the Japanese Council of Ministers in 2017, and the price of hydrogen considering carbon neutrality in FY2030 is expected to be 3000 $/ton[14]. In anticipation of the commercialization of methane hydrate in FY2030, this model sets the sales price by aligning the price per calorific value with this value.

Table 4. Precondition of methane hydrate development.

Field data	
Original gas in place	591 million m^3
Water depth	780 m
Distance from Shore	50 km
Production information	
Production periods	20 years
Number of wells	24
Energy price	
Electricity	90 $/MWh
Hydrogen	3000 $/ton
Ammonia	480 $/ton

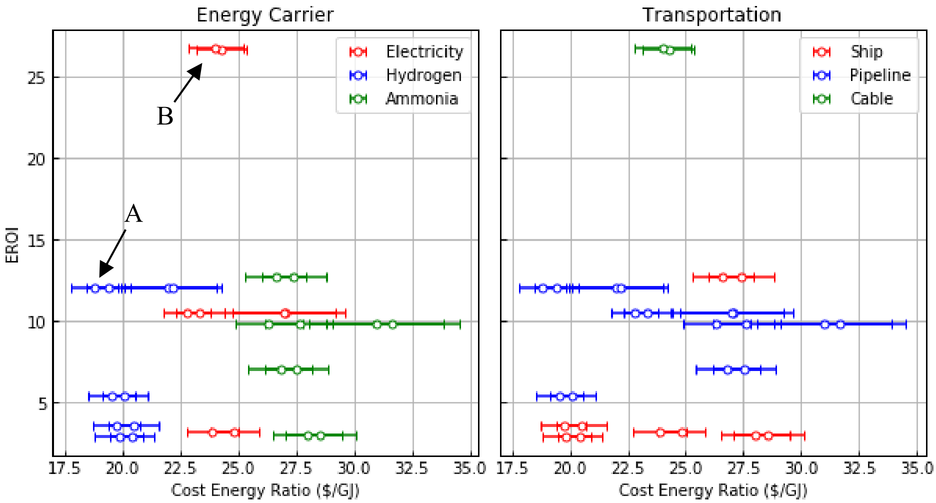

Figure 1. Comparison of development concepts by attribute.

The 28 development concepts are plotted for each attribute from the simulation results in Fig 1. The two figures show the same evaluation results, but they are color-coded for each attribute, and the error bars indicate the variability (within the 95% confidence interval.) The production cost is set on the horizontal axis and the EROI on the vertical axis. The production cost shows the sum of CAPEX and OPEX for 20 years per amount of energy output.

In terms of production cost, the evaluation of development concept A was the highest at 18.8 $/GJ. For EROI, development concept B has the highest rating of 26.7.

4. Discussion

The 28 development concepts are plotted in Fig 1 for each attribute. The two figures show the same evaluation results, but they are color-coded for each attribute, and the error bars indicate the variability (within the 95% confidence interval.) The production cost is set on the horizontal axis and the EROI on the vertical axis. The production cost shows the sum of CAPEX and OPEX for 20 years per amount of energy output.

It is effective for narrowing down the list of promising development concepts because the relative evaluation of the development concepts can be calculated by using the simulation model, and the promising concepts can be judged. In particular, it is effective in establishing a means to evaluate concepts with a low level of technological maturity while allowing for uncertainty. However, the workshops' ideas as knowledge and stakeholders' knowledge and opinions must be evaluated and discussed in the simulation model, and expansion of the model is an issue for the future.

5. Conclusion

In this paper, we propose a co-creative approach engaging various stakeholders through workshops and model-based discussion. The workshop was designed to gather ideas from stakeholders from various backgrounds. The ideas raised in the workshops were analyzed to construct a morphological matrix to generate a comprehensive solution space. A total of 117 ideas and comments were collected in the Bias Breaking Workshop, and the level of understanding among the participants was improved.

A simulation model was developed to quantitatively evaluate the wide variety of concepts, by integrating several element models, such as economic evaluations models, gas production models, and production system models. The model interface was designed to support the understanding of the complex system. The 28 development concept results are compared from the model, and promising development concepts are estimated.

6. Future work

In this study, the workshops were conducted mainly with experts, but it is necessary to gain the understanding of residents and other stakeholders to promote the decision-making process in a broader sense.

The simulation models were developed to evaluate the concepts proposed by the MH21-S Strategic Commercialization Team. However, it is required to extend the model to meet the needs of stakeholders and to aim for social decision-making by conducting interactions with stakeholders based on the model.

7. Acknowledgment

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8. Reference

[1] N.N., *The Future of Methane Hydrate Development (in Japanese)*, The Ministry of Economy, Trade, and Industry, https://www.meti.go.jp/shingikai/enecho/shigen_nenryo/pdf/022_03_00.pdf , accessed: 06.03.2022.

[2] E. Meyer, Being the Boss in Brussels, Boston, and Beijing, *Harvard Business Review*, 95, 2017, No. 4, pp. 70–77.

[3] R. Wada and K. Takagi, Co-creation Platform for Enhancement of Japanese Offshore Technology (in Japanese), *Journal of the japan society of naval architects and ocean engineers*, Vol 2016, 24, pp.259-270

[4] Y. Matsudaira, R. Wada, Y. Konno, G. Hashimoto and K. Takagi, Exploring Promising Concepts and Critical Technologies for Offshore Methane Hydrate Development System, *Advances in Transdisciplinary Engineering*, 2019, Vol. 10, pp. 242–251.

[5] N. Tomoki, *Extended Evaluation of Assumed Systems and External Environmental Factors in Methane Hydrate Production Using a Systems Approach*, The University of Tokyo, bachelor thesis, 2020

[6] M. Misa, *Development of an Economic Evaluation System for Methane Hydrate Development Projects Considering Uncertainty*, The University of Tokyo, bachelor thesis, 2021

[7] I. Tatsuki, *Uncertainty analysis of system production capacity according to methane hydrate reservoir characteristics*, The University of Tokyo, bachelor thesis, 2021

[8] B. Cameron, E. Crawley and D. Selva, *Systems Architecture. Strategy and product development for complex systems*, Prentice Hall Press, One Lake Street Upper Saddle River, 2016

[9] S. Peng, L. Pelegrin, P.A. Luna, H. Horii and B.R. Moser, Problem Exploration with Bias Breaking Ideation for Maritime Emissions Reduction, *Advances in Transdisciplinary Engineering*, 2019, Vol. 10, pp. 115–124.

[10] K. Yamamoto, M. Abe, N. Temma, Issues to Realize Carbon Neutral in Methane Hydrate Resource Development in Japanese Water, *Energy and resources*, 2021, Vol 42, pp 376—381.

[11] P.B. Paulus, R.M. Korde, J.J. Dickson, A. Carmeli and R. Cohen-Meitar, Asynchronous brainstorming in an industrial setting: Exploratory studies, *Human factors*, 2015, 57, No. 6, pp. 1076–1094.

[12] N. Hall and S. Delille, Cost estimation challenges and uncertainties confronting oil and gas companies, *AACE International Annual Meeting, Atlanta, AACE International Transactions*, EST, 4912011, 15–19.

[13] N.N., *Study of MH Production System and Evaluation of Economics and EROI, Comprehensive Report of Phase 2&3 Research Results*, Research Consortium for Methane Hydrate Resources in Japan (MH21), Section IV, 2022. https://www.mh21japan.gr.jp/mh21wp/wp-content/uploads/phase2_3_ 6_1e.pdf accessed: 06.03.2022.

[14] M. Council, Basic Hydrogen Strategy, 2017, https://www.meti.go.jp/english/press/2017/pdf/1226_003b.pdf, Accessed on 01.15.2022