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Research and Suggestions on Economic and Comprehensive Benefit Evaluation of LNG Cold Energy Utilization in the Context of Energy Transition#

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ABSTRACT

In the context of the accelerating global sustainable and low-carbon energy transition, maximizing the utilization of the cold energy value inherent in LNG holds significant importance for enhancing the competitiveness of corporate industrial chains and high-quality energy mitigation development. Given the diverse types, varying scales, and complex business cooperation models of LNG cold energy utilization, this research focuses on four major types: cold energy power generation, cold energy storage station, cold water aquaculture, and liquid air energy storage. By considering policy, methodology, and models, and taking into account economic, energy, and environmental factors, the study adhered to the principle of "seeking common ground while reserving differences, emphasizing key points". Optimal techno-economic evaluation methods and key evaluation indicators were selected, and constructs energy substitution modules, carbon sink trading modules, and policy guarantee modules were built. An economic and "3E" comprehensive benefit evaluation method for LNG cold energy utilization project was formed, and suggestions for promoting the development of cold energy business from a technical and economic perspective were also provided. The research findings could promote the implementation of LNG cold energy utilization project, providing reliable references and insights to prevent the waste of cold energy resources

Keywords: LNG cold energy utilization, recovery and utilization, economic benefits, comprehensive benefits

NONMENCLATURE

Abbreviations	
CBE	Comprehensive benefit evaluation
CE	Cold energy
CEU	Cold energy utilization

1. INTRODUCTION

The utilization of LNG CE started in Japan in 1979. After decades of research and development, Japan has become the world's leading country in CEU, accounting for 50% of the industry share in global effective CE projects. China started late in the research on CEU. As of October 2023, about only 10 LNG CEU projects have been put into production or started construction in China. The potential market for LNG CEU in China is huge, estimated to reach 21.8 billion yuan by 2028, with a compound annual growth rate of 10.9%[1]. Compared with conventional LNG projects, LNG CEU project have various characteristics, such as diverse utilization scales, complex utilization scenarios, different engineering solutions involved in different reliance conditions, types/quantities/prices of supporting equipment and facilities, business models, cost structures, types of income, etc.[2-3]. When planning and making investment decisions for projects, more factors need to be considered. At present, there are enough domestic researches on LNG CEU technology[4-5], and the problem is that few researches on its investment, economic evaluation modules, methods, indicators, etc., and enterprises are lacking references when planning and making investment decisions for complex CEU project.

This paper mainly focuses on four types of LNG CE applications: CE power generation, liquid air energy storage, cold water aquaculture, and CE storage station. Guided by evaluation needs, and selects corresponding evaluation methods, clarifies related parameters and indicators, and establishes applicable investment and economic evaluation models. It also studies the energy, economic, and environmental CBE methods for LNG CEU project from a broader perspective, to support project investment planning and scientific decision-making. At the same time, it proposes relevant suggestions from a techno-economic perspective to promote the development of LNG CEU business, in the hope of providing support for industrial development.

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2. FINANCIAL EVALUATION METHOD FOR LNG CEU

The economic benefit evaluation result is a crucial basis for project investment decisions. To meet the development needs of LNG CEU project and standardize their economic evaluation process, this section selects evaluation methods, clarifies evaluation parameters and indicators based on the characteristics of various LNG CEU project[6-7], and modularizes specific factors to establish an reliable evaluation model. This approach ensures the quality of project evaluation and enhances the scientific level of decision-making.

The main contents of the economic evaluation for LNG CEU project should include: project investment estimation, cost estimation, revenue and major tax estimation, financial analysis, uncertainty analysis, and economic comparison of alternatives. Studies have shown that the CE projects economic evaluation methods are similar to those of conventional LNG projects. Therefore, the primary research focuses on the differences in investment/cost/revenue estimation and economic benefit growth points of LNG CEU project. The main methods and parameters are summarized as follows.

2.1 Investment Estimation

The investment estimation for LNG CEU project is a core element of investment analysis. It requires a comprehensive consideration of estimation methods, construction content, design depth, technical solutions. Some key aspects such as the necessity of construction, project scale, market demand, reliance on LNG receiving terminals (including gasification and external transmission volumes, vaporizer configurations, etc.), design schemes, and design division of labor.

The key focus areas for overview analysis in various directions of CEU has summarized in Table 1 below.

Based on the actual conditions of the project and the depth of design, organize the input requirements for preparation, including quantity templates, cost requirements planned by the construction unit, prices of major equipment and materials, exchange rates, transportation, miscellaneous rates, and etc. Conduct research on the project's Work Breakdown Structure and Cost Breakdown Structure. Common estimation methods for LNG CEU project include the production capacity index method, the proportional estimation method, and the index estimation method. Once the basic data and estimation methods for the technical scheme of the CEU project are determined, the construction investment components are divided into engineering costs, other construction costs, and contingency costs. Each cost item is then determined one by one, thus completing the investment estimation.

Table 1 Key Understanding Information of LNG CEU project

CE Power Generation	CE Storage Station	Cold Water Aquaculture	Liquid Air Energy Storage
1. Availability of Gasification Facilities and Reserved Interfaces; 2. Addition of Propane Flare System; 3. Power Generation Capacity; 4. Equipment Procurement Strategy and Import Requirements for Turbine Generators; 5. Dependency on Utility Systems.	1. Cold Utilization Scenarios; 2. Cooling Capacity; 3. Distance between Cooling Client and CE Storage Station; 4. Coolant Medium; 5. Pipeline Material.	1. The suitability of the original receiving station area to accommodate the site scale and conditions for cold-water aquaculture; 2. Aquaculture Plan; 3. Aquaculture Scale; 4. Business Model.	1. Availability of Supporting High-pressure Export Facilities and Reserved Interfaces; 2. Energy Storage Scale; 3. Market Situation; 4. Business Model; 5. Whether Land Acquisition is involved.

2.2 Cost/Revenue Estimation

The total cost estimation for LNG CEU project typically employs the "production cost plus period expense method." The total cost primarily includes expenses for purchased raw and auxiliary materials, personnel costs, repair costs, loss costs, safety production costs, other manufacturing costs, other management costs, system standby costs, insurance costs, operating costs, depreciation costs, amortization costs, and financial costs.

LNG CEU projects are generally constructed in conjunction with receiving terminal projects. The production and operation can rely on the existing resources of the receiving terminal, thereby reducing the operating costs of the CEU project. Personnel costs, other manufacturing costs related to staffing, other management costs, safety production costs, and insurance costs can be considered based on the specifics of the project. CE power generation projects, which utilize surplus energy (such as residual pressure, residual heat, and residual gas) to build captive power plants, should determine whether to include system standby costs for the captive power plant according to the requirements of government documents at the project location.

From the revenue perspective, currently, CE power generation and liquid air energy storage projects increase the power supply to the receiving terminal by recovering CE, thereby reducing the amount of purchased electricity. The savings from self-generated electricity are considered as project operating income. The electricity usage during the receiving terminal's operational cycle is divided into peak, high, flat, and low periods, and revenue is calculated based on the time-of-use electricity prices for commercial and industrial users in the project location.

For CE storage station projects, revenue is generated by supplying CE to downstream users (such as cold storage facilities, data centers, etc.) and charging for the CE supplied. Cold water aquaculture project revenue mainly comes from selling aquaculture products such as fish eggs, fry, and mature fish.

2.3 Economic Growth Points

The main benefits of the CE project are reflected in the replacement of traditional power generation methods for producing CE, and the replacement of traditional grid power by generating electricity using CE. While generating clean energy, it can also contribute to carbon reduction for the receiving station or other users of CE. Besides the carbon reduction benefits brought by the CE project itself, from the perspective of the operation of the LNG receiving station, developing a CE project can also save electricity costs by reducing the use of seawater pumps. Therefore, in addition to the main business revenues (savings from self-generated electricity, revenue from surplus electricity sold to the grid, cooling supply revenue, etc.), the additional income growth points of the LNG CEU project can be summarized as including carbon reduction benefits, energy replacement benefits, and policy subsidy benefits. Due to the different specific dependencies of each project and the different policies in different regions, these three growth points will be modularized into the energy replacement module, carbon trading module, and policy guarantee module.

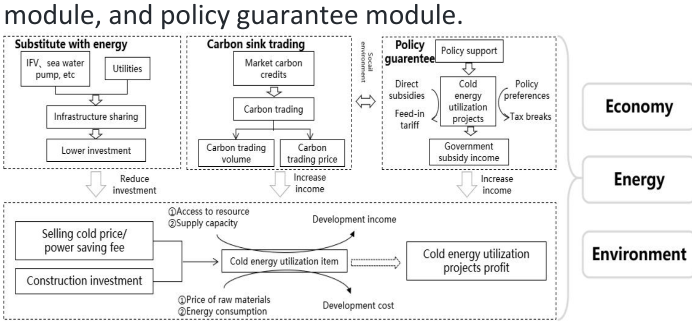

Figure 1 Modular composition of each link in the evaluation of LNG CEU project

2.3.1 Carbon Sequestration Trading Module:

Starting from the carbon reduction achieved after the implementation of the CE project, the carbon reduction quantity is quantified by comparing the energy consumption of producing CE products using CE methods versus traditional power supply methods, based on the scale of the CE project. The reduced carbon emissions can be economically valued in the form of carbon emission rights transfer income, using the emission rights trading prices from various national carbon trading pilot markets as the basis for quantifying the economic value. The calculation methods for carbon reduction in different application scenarios after the implementation of CE projects are as follows:

(1)CE Storage Station (Cooling for Data Centers, Cold Storage, etc.):Determine the annual electricity consumption required to produce sufficient CE for unit projects based on the number of data center cabinets, the cooling scale of cold storage, etc. After switching to CE cooling, calculate the electricity saved over the entire lifecycle, and multiply by the power carbon emission factor to calculate the reduced carbon emissions. The carbon reduction benefits need to determine the beneficiaries based on the investment entity, cooling entity, and cooling user situation.

(2)Cold Water Aquaculture: Determine the annual electricity consumption required to maintain the water temperature of the aquaculture ponds based on the scale. Calculate the electricity saved using CE cooling, and multiply by the power carbon emission factor to calculate the reduced carbon emissions.

(3)CE Power Generation: Compare the electricity generated by CE power generation with the situation of using external grid power without the CE power generation project. Calculate the electricity saved and the reduced carbon emissions over the entire life cycle of the project after using CE power generation.

In the above scenarios, carbon emissions generated by the CE project itself need to be considered. The final carbon reduction quantity is obtained by subtracting the carbon emissions generated by the CE project itself from the carbon reduction quantity achieved by replacing the traditional project.

2.3.2 Energy Substitution Module:

In the process of CEU, intermediates such as ethylene glycol are typically used for heat exchange and vaporization of LNG, partially replacing the process of using seawater pumps to extract seawater for heat exchange and vaporization of LNG. Therefore, developing CE projects can reduce the operating time of seawater pumps, thereby lowering electricity costs. The calculation formula is as follows:

Energy Substitution Benefit = Annual Energy Substitution Quantity (kWh) × Electricity Price (yuan/kWh, excluding tax)

2.3.3 Policy Guarantee Module:

For government subsidy funds, analyze whether to include subsidy income based on the government policies in project location. The calculation formula is as follows: Subsidy Income = Per kWh Subsidy Income (yuan/kWh) × Annual Electricity Generation (kWh)

3. COMPREHENSIVE BENEFIT EVALUATION METHOD FOR LNG CEU

As a typical representative of energy-saving and emission-reduction projects, LNG CEU has received significant attention. However, focusing solely on the project's economic return can easily overlook the environmental protection goals of energy-saving and emission reduction, thereby amplifying the conflict between project construction and environmental protection efforts. Therefore, there is an urgent need to reasonably evaluate the comprehensive benefit level of LNG CEU project to enhance the rationality of corporate decision-making. This section selects appropriate evaluation methods, optimizes evaluation indicators, standardizes and calculates the weights of each indicator, and finally derives the comprehensive benefit levels of LNG CEU project of various typical scales.

3.1 Comprehensive Benefit Evaluation Indicators

Based on the characteristics of various CEU project, the "3E" coupling coordination degree method[8] is selected to study the balanced and coordinated relationship among the economic (Economy), energy (Energy), and environmental (Environment) dimensions of the projects. Starting from the "goal level-criterion level-indicator level," the CBE indicators of the main dimensions, such as economy, energy, and environment, are optimized (Table 2). A "+" indicates that a larger value of the indicator is better, while a "-" indicates that a smaller value of the indicator is better.

Table 2 Index System for Comprehensive Benefits of LNG CEU project

Objective Level	Criterion Level	Main Dimensions	Indicator Level	Nature
Energy - Economy-Environment Development Level	**Economy Subsystem**	Revenue	Sales Revenue	+
			After-tax net cash flow	+
		Cost	Operating expenses	-
			Value-added tax and surcharges	-
		Operational Capacity	Working capital	+
			Financial expenses	-
			Debt-to-asset ratio	-
			Accumulated surplus funds	+
	Energy Subsystem	Energy Consumption	Electricity consumption	-
			Electricity rate	-
			Water consumption	-
			Water rate	-
		Energy Production	Electricity sale volume	+
			Electricity sale price	+
			Cooling capacity	+
			CE price	+
	Environment Subsystem	Emission Reduction	CO2 emission reduction volume	+
			CO2 transaction price	+
			Propane emission reduction volume	+
			Propane transaction price	+

3.2 Evaluation Method

To eliminate the evaluation errors caused by the nature of the indicators, the range method[9] is first used to standardize the indicator data. Depending on whether the impact of the evaluation indicators is positive or negative, the two formulas in Equation 1 are used to ensure the consistency of indicator evaluation. Here, i and j represent the month and the indicator, respectively; x_{ij} and x'_{ij} are the raw data and standardized data of the j-th indicator in the i month(i=1,2,3...,k); $\max(x_j)$ and $\min(x_j)$ are the maximum and minimum values of the j-th indicator, respectively.

$$x'_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}$$

$$x'_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \qquad \text{Equation(1)}$$

Based on the results of data standardization, the entropy weight method[10] is used to objectively assign weights to the evaluation indicator system for the synergistic development of economic benefits and environmental protection in LNG CEU project. This approach helps to avoid the evaluation errors associated with subjective assessment of indicators (see Equation 2). Here, k and n represent the sample size of LNG CEU project and the number of indicators, respectively; x'_{ij} represents the standardized data; H_j represents the information entropy of the j-th indicator; and W_j represents the weight assigned to the j-th indicator.

$$p_{ij} = \frac{x'_{ij}}{\sum_{j=1}^{n} x'_{ij}} \qquad H_j = -\frac{1}{\ln(k)}\sum_{i=1}^{k} p_{ij}\ln(p_{ij})$$

$$W_j = -\frac{1-H_j}{\sum_{j=1}^{k}(1-H_j)}$$ Equation(2)

Based on the objective weighting of evaluation indicators and considering the intrinsic connections between different systems, the coupling coordination degree of the "energy-environment-economy" for LNG CEU project is comprehensively evaluated according to Equations 3 to 6. This evaluation is used to determine the degree of synergistic development between economic benefits and environmental protection in project investment and construction, thereby proposing targeted countermeasures and suggestions. Among them, F_j represents the comprehensive score level of the *j*-th indicator; F_1、F_2、F_3 respectively represent the comprehensive benefits of the energy subsystem, economic subsystem, and environmental subsystem; C is the coupling degree of the "energy-environment-economy" for LNG CEU project; T is the comprehensive evaluation index of economic benefits and environmental protection for LNG CEU project; D is the calculated result of the coupling coordination degree of the "energy-environment-economy" for LNG CEU project; α 、 β 、 δ are the contribution shares of different systems in the 3E coupling coordination model. Considering the equal importance of the development of energy, economy, and environment in LNG CEU project, this paper assumes the values of α 、 β 、 δ to be 1/3. Thus, the evaluation results of the cross-system coordinated development degree between economic development and environmental protection for LNG CEU project can be obtained.

$$F_j = \sum_{j=1}^{n}(w_j \times p_{ij})$$ Equation(3)

$$C = \left\{ \frac{F_1 F_2 F_3}{\left(\frac{F_1 + F_2 + F_3}{3}\right)^3} \right\}^{\frac{1}{3}}$$ Equation(4)

$$T = \alpha F_1 + \beta F_2 + \delta F_3$$ Equation(5)

$$D = \sqrt{C \times T}$$ Equation(6)

After obtaining the evaluation results of the comprehensive benefits of the LNG CEU project, targeted optimization efforts can be carried out to maximize the comprehensive benefits of the investment in the LNG CEU project.

4. APPLICATION EXAMPLE

Using the cooling capacity of a single LNG vaporization line in a conventional receiving terminal project (LNG processing capacity of approximately 180 tons per hour) as the basic condition, and considering the approximate temperature range utilization, analyze the economic and comprehensive benefits of four LNG CEU projects scenarios..

According to the economic benefit analysis results, for the same LNG vaporization volume:

- The LNG CE power generation project has a smaller construction scale and lower investment. Especially when relying on IFV vaporization devices, the project shows better economic viability.
- For the CE storage station project, if only considering data center cooling, the construction investment is significantly lower than when considering the comprehensive cooling of data centers, freeze-dried fruits and vegetables, and cold storage. Under the same internal rate of return, the cooling price calculation shows that data center cooling is more economically viable.
- The liquid air energy storage project has a high investment, but also high operating income, resulting in the shortest payback period.

Table3 Economic Analysis of Different CEU project under the Same Cooling Scale

Cost/Indicators	CE Power Generation		CE Storage Station (data centre)	CE Storage Station (Cold storage, Freeze dried fruits and vegetables)	Liquid Air Energy Storage
	With IFV	Without IFV			
Internal Rate of Return(%)	8.01%	6.03%	6%	6%	13.9%

By conducting a comprehensive benefit analysis of the above projects, it can be found that the CBE efficiency level is "CE storage station project > liquid air energy storage project > CE power generation project." Among these, the CE power generation project has relatively good coupling coordination in the early stages, but it declines significantly in the mid to late stages, with higher investment uncertainty. In contrast, the coupling coordination level of the liquid air energy storage project and the CE storage station project shows an overall upward trend. The coupling coordination degree of the comprehensive benefits of the CE storage station project is significantly better than that of the liquid air energy storage project, indicating significant potential for project investment and operational development.

Therefore, in the investment decision-making of LNG CEU project, under the condition of similar project returns, appropriate attention should be paid to the investment opportunities of the CE storage station project to maximize the total factor productivity of economic benefits and environmental protection for the enterprise.

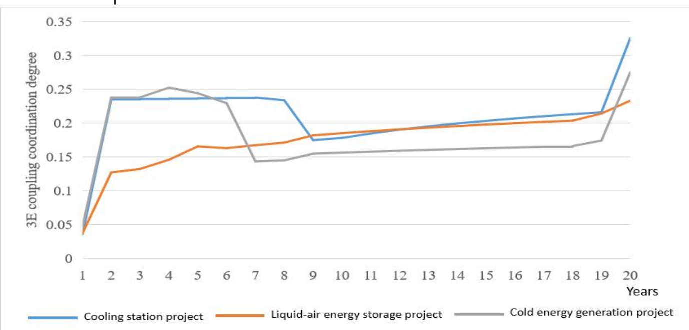

Figure 2 CBE Results of LNG CEU project

5. CONCLUSION

The study focuses on optimizing and summarizing methodologies for estimating investment costs, and revenues for LNG CEU projects in four main areas: power generation, storage station, liquid air energy storage, and cold water aquaculture. It constructs flexible modules for energy substitution, carbon sink trading, and policy support, forming a comprehensive economic evaluation model.

By optimizing the "3E" coupling coordination evaluation method, which considers energy, economy, and environment and using the range and entropy weight methods, a CBE method for LNG CEU projects is established. This enhances the scientific nature of enterprise planning and decision-making.

LNG CEU can significantly improve energy efficiency and reduce energy consumption, aligning with national energy transition and carbon reduction goals. Enterprises should consider the environmental and social benefits of carbon reduction and energy substitution in their economic evaluations and actively promote CE projects.

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